LUX

Linac/Laser-based source for Ultrafast X-rays

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for the LUX design study team

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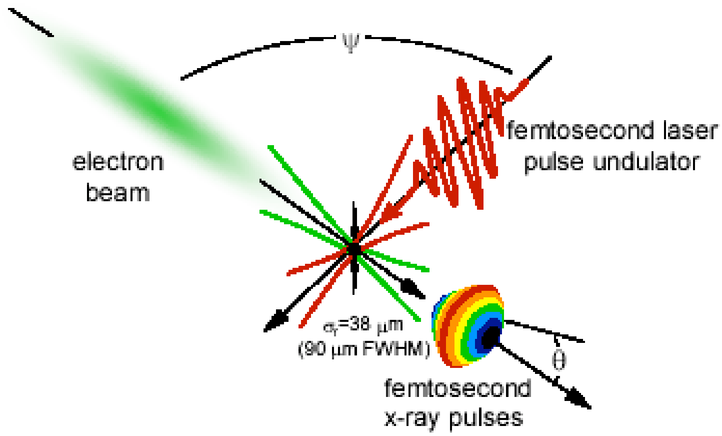
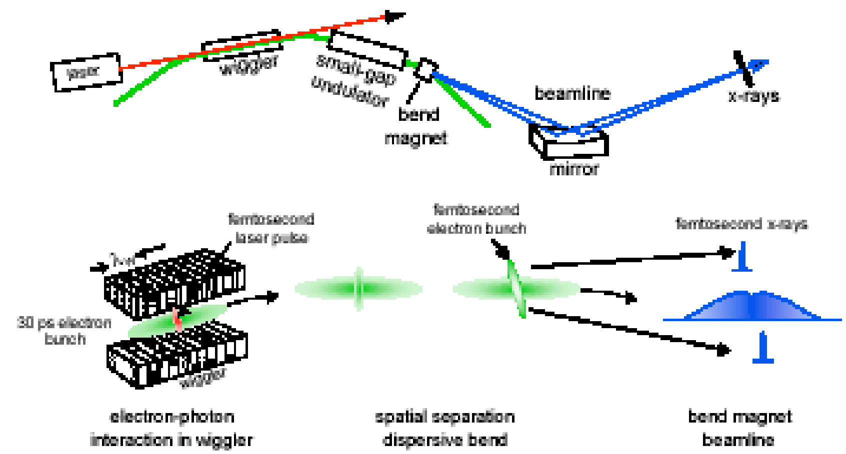
LUX is the latest development in LBNL's history of ultrafast x-ray facilities



Thomson scattering



Laser slicing R. Schoenlein poster

- Kim, K.-J., S. Chattopadhyay, and C.V. Shank, "Generation of femtosecond x-ray pulses by 90 degree Thomson scattering", Nuc. Inst. and Meth. in Phys. Res. A, 1994. 341: p. 351-354.
- Zholents, A.A. and M.S. Zolotorev, "Femtosecond x-ray pulses of synchrotron radiation", Phys. Rev. Lett., 1996. 76(6): p. 912-915.
- Leemans, W.P., et al.," X-ray based time resolved electron beam characterization via 90° Thomson scattering", Phys. Rev. Lett., 1996. 77(20): p. 4182-4185.
- Schoenlein, R.W., et al., "Femtosecond x-ray pulses at 0.4 angstroms generated by 90° Thomson scattering: A tool for probing the structural dynamics of materials.",Science, 1996. 274: p. 236-238.
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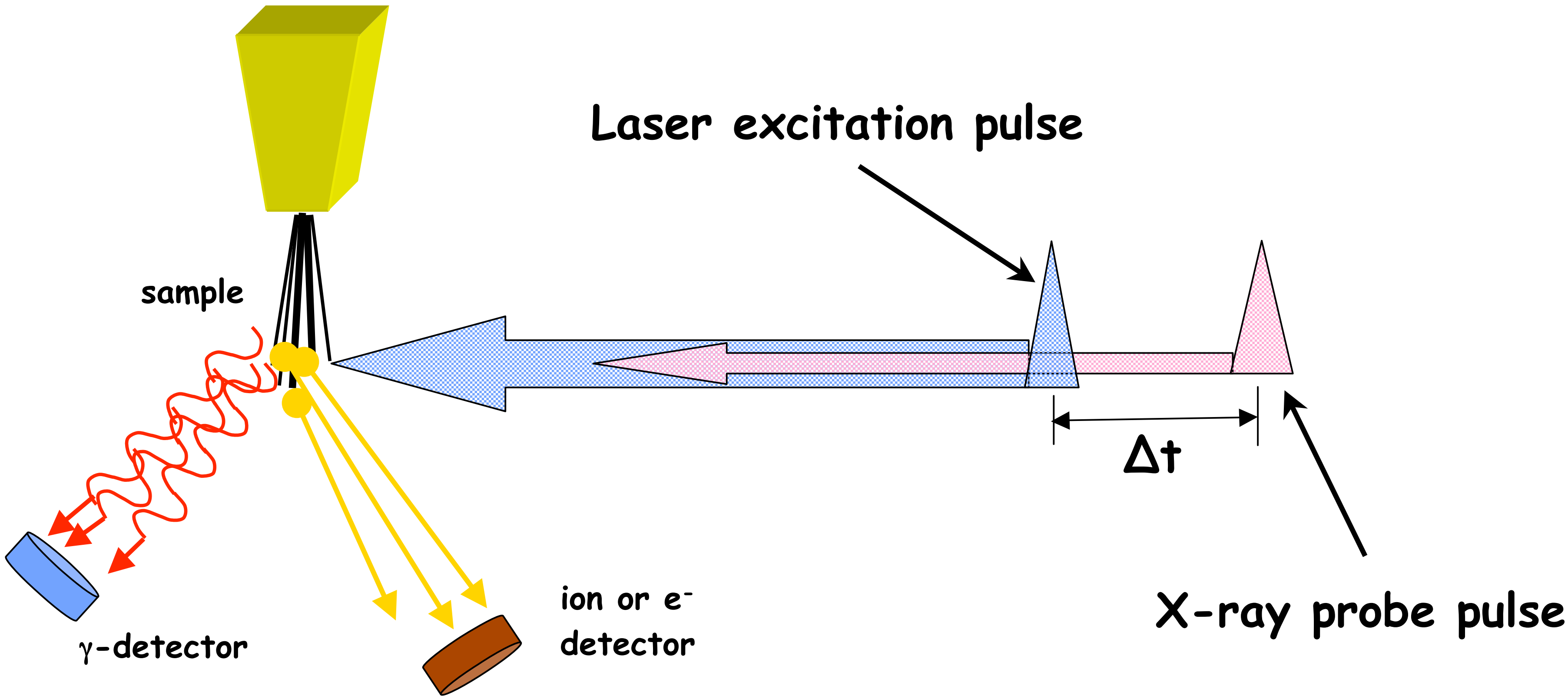
- Schoenlein, R.W., et al.," Generation of x-ray pulses via laser-electron beam interaction", Appl. Phys. B, 2000. 71: p. 1-10.
- Schoenlein, R.W., et al.," Generation of femtosecond pulses of synchrotron radiation", Science, 2000. 287: p. 2237-2240.

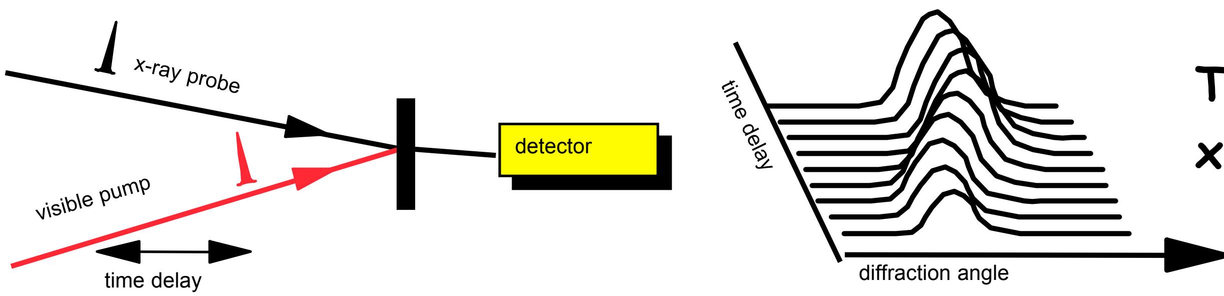
LUX facility concept for time-resolved spectroscopies



- Ultrafast laser pulse "pumps" a process in the sample
- Ultrafast x-ray pulse "probes" the sample after time Δt
    - Ultrafast lasers an integral part of the facility
    - Synchronized x-ray and laser pulses
- Multidimensional spectroscopies e.g. 3 laser pump beams and an x-ray probe
- Two x-ray wavelengths

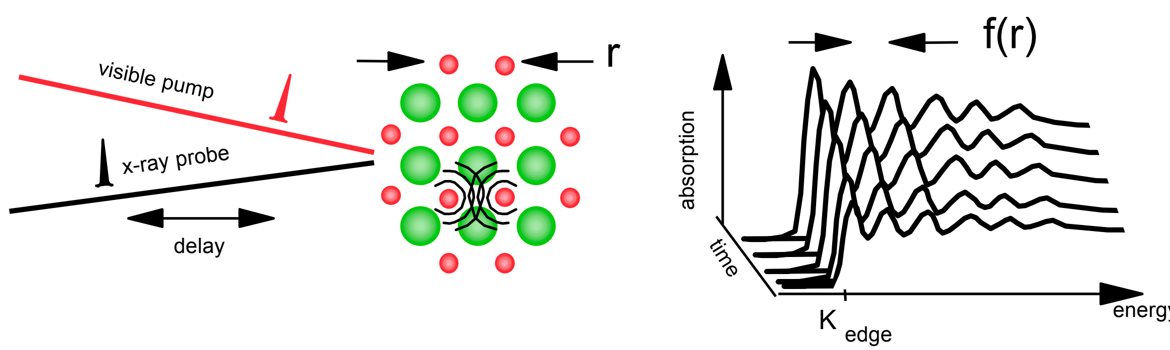
A refined tool supporting a range of techniques for structural dynamics applications

- Combines diffraction and spectroscopy
  - Nuclear positions and electronic, chemical or structural probes



Time-resolved x-ray diffraction

Time-resolved EXAFS NEXAFS

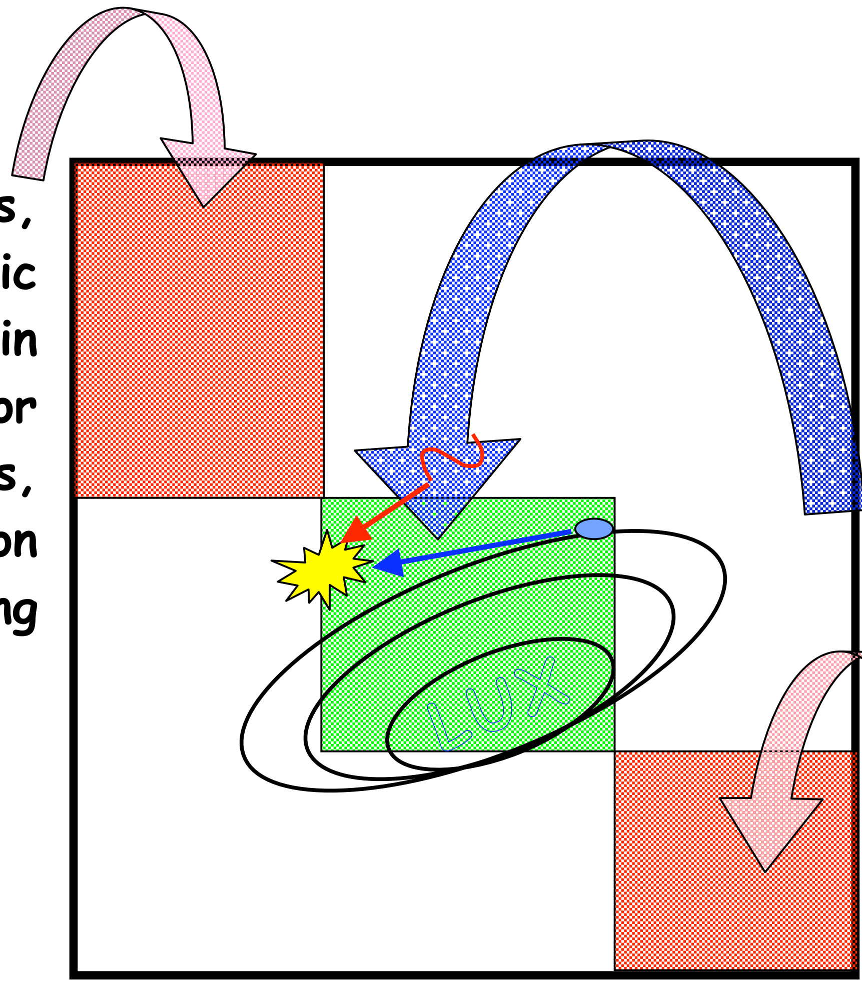


Plus photoelectron spectroscopy, photoemission microscopy, etc

- Access new science in the time-domain x-ray regime
- Time dynamics parameters have not been widely exploited in the x-ray, mostly due to lack of sources

Repetition rate vs. energy per pulse

MHz-GHz, nJs, limited by acoustic velocities in samples, good for counting expt's, photoemission imaging



1 kHz-100kHz, μJs ideal match to ultrafast lasers and sample relaxation / replenishment considerations, single photon regime modest power, avoid sample damage, high signal averaging rate

X-ray pulse repetition rate

X-ray pulse energy

10-100Hz, mJs, limited by sample damage, many high field effects

We propose a facility for ultrafast dynamics which is driven by scientific requirements

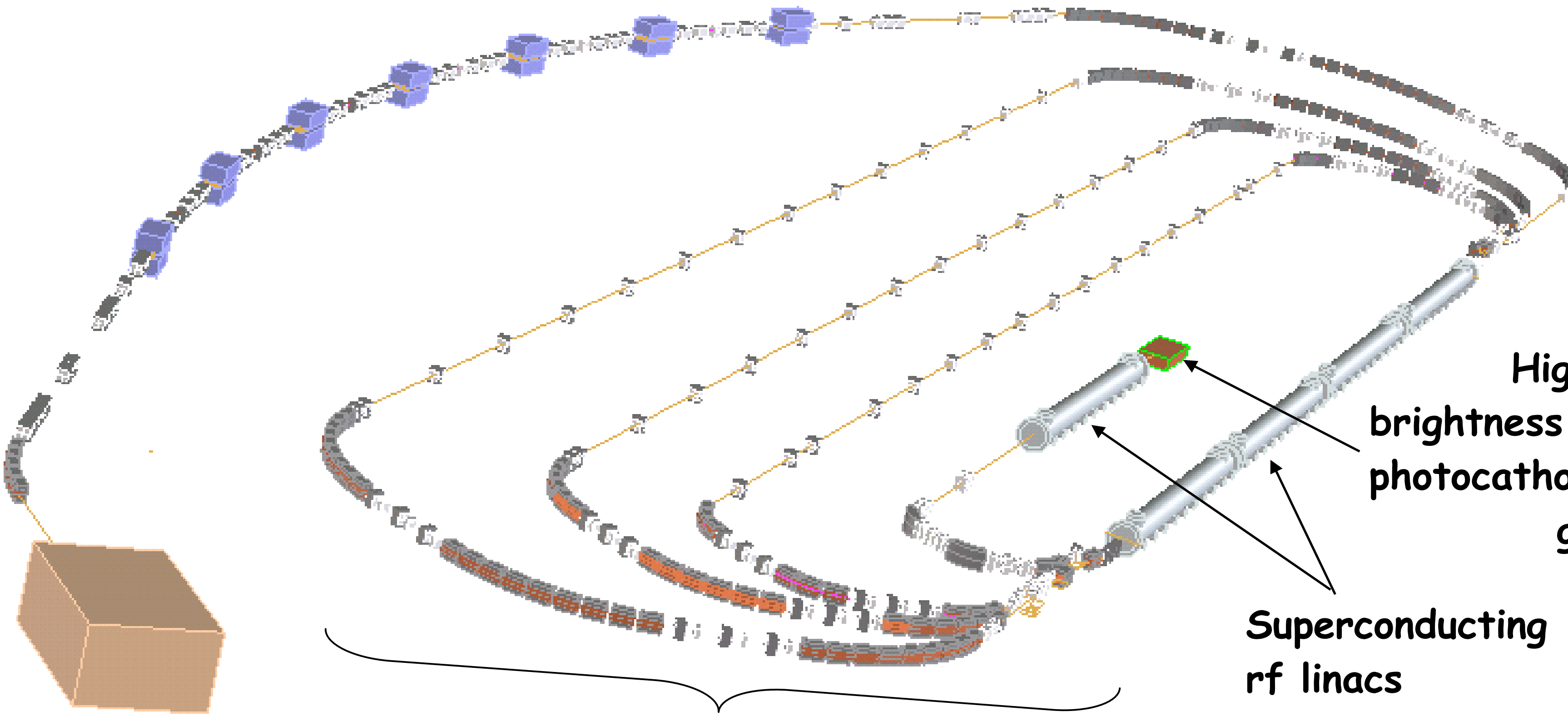
• Pulse duration	10-200 fs variable, *< 1 fs in future*
• Flux per pulse	~10^{6}-10^{13} (ph/pulse/0.1%BW)
• Photon range	20 eV to 12 keV
• Tunability	independently tunable beamlines
• Repetition rate	10 kHz to match pump-probe experiments
• Power desnity	10^{15} Wcm^{-2} achievable
• Synchronization	10's fs pump laser – probe x-ray
• Polarization	lhc, rhc soft x-ray / linear hard x-ray
• Multiple laser systems	Master oscillator
	Photocathode laser
	FEL seed laser
	Beamline endstation pump lasers
• Number of beamlines	~ 20 independent beamlines

There are many proposed ultrafast x-ray projects around the world

- LCLS*: SASE FEL (funded)
- BNL DUV FEL*: harmonic generation in FEL from laser seed (operational)
- DESY TTF-II: linac-based SASE FEL (funded)
- BESSY FEL: harmonic generation in FEL from laser seed
- SPPS*: spontaneous emission from short bunches (operational)
- ALFF: Argonne linear FEL, SASE soft x-ray
- European X-ray FEL: SASE FEL
- Daresbury 4GLS: single-pass energy recovery linac with variety of x-ray sources under consideration
- Cornell / TJNAF ERL*: single-pass energy recovery linac optimized for diffraction limited undulator radiation and high average power
- MIT-Bates X-ray FEL: single-pass linac with seeded and SASE FEL's
- Arc-en-Ciel*: linac based, recirculation or energy recovery mode, SASE and seeded FEL's
- FERMI@Elettra: linac-based FEL
- BNL PERL: energy recovery linac

* Presentations at this meeting

LUX accelerator design is based on a *recirculating linac*



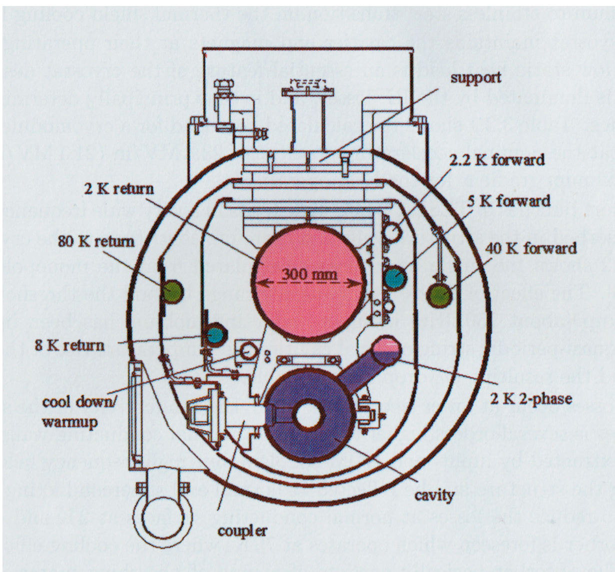
Beam dump absorbs ~ 30 kW beam power

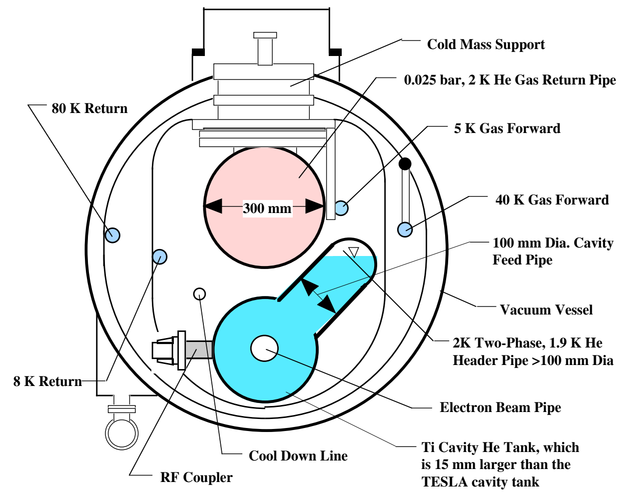
Magnetic arcs transport each energy beam

Retain option for energy recovery by building the final arc

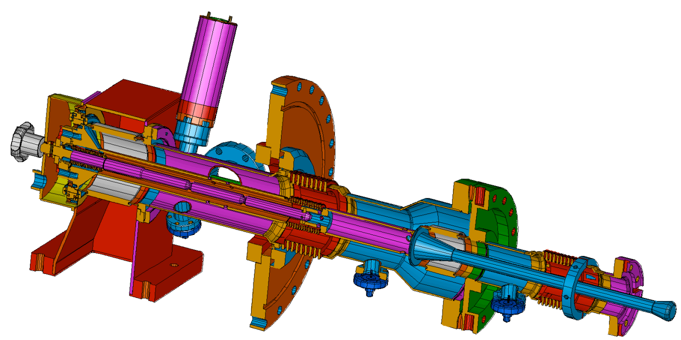
Accelerating linac cw power considerations, based on TESLA technology

- Filling time > time between bunches - operate in cw mode
  - Thermal connection from cavity bath to He supply to accommodate dynamic heat load ~40 W/cavity
    - Increase diameter, or additional connectors to liquid He supply

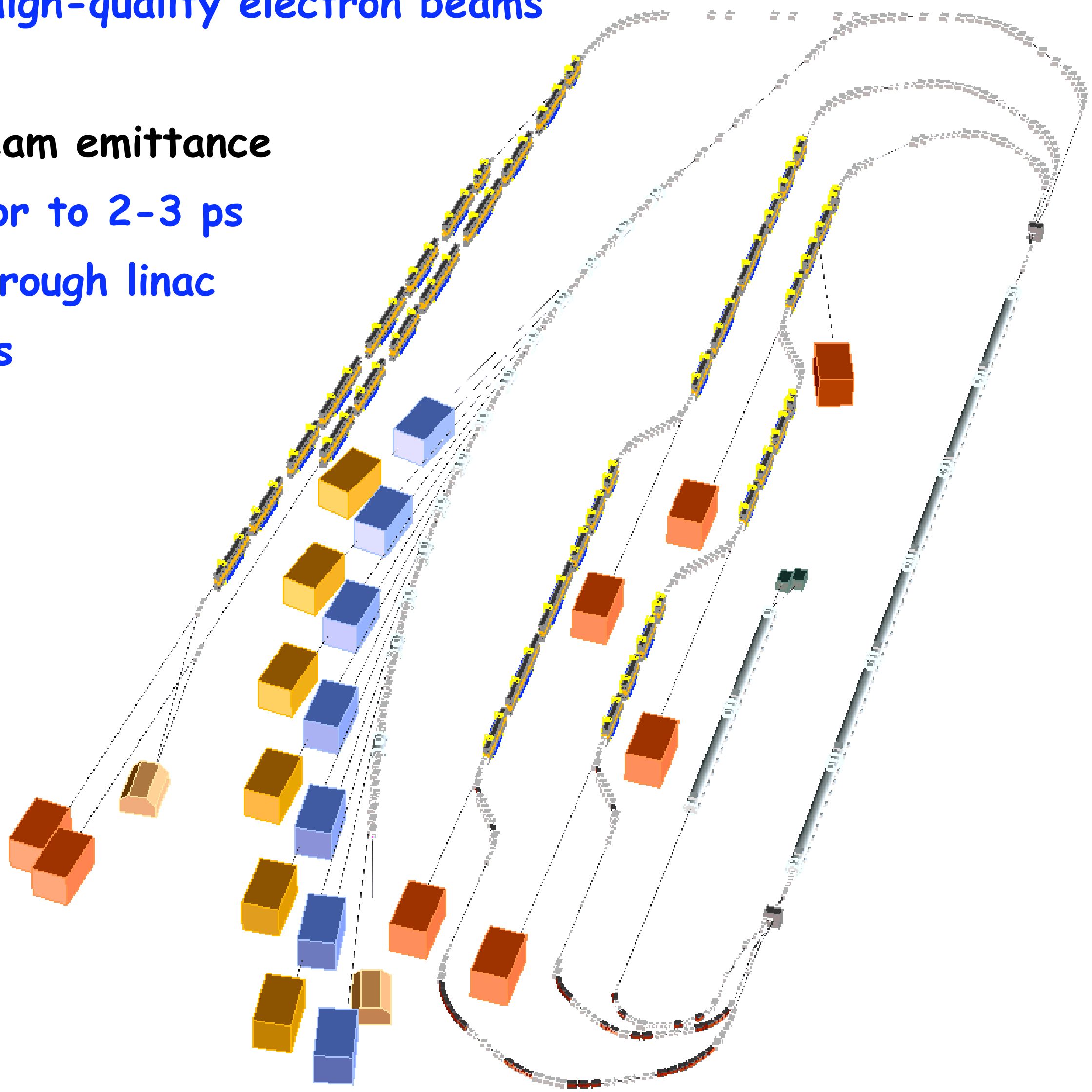




- Input coupler
  - 10 – 20 kW CW



LUX based on a recirculating linac provides a refined source of ultrafast x-ray pulses



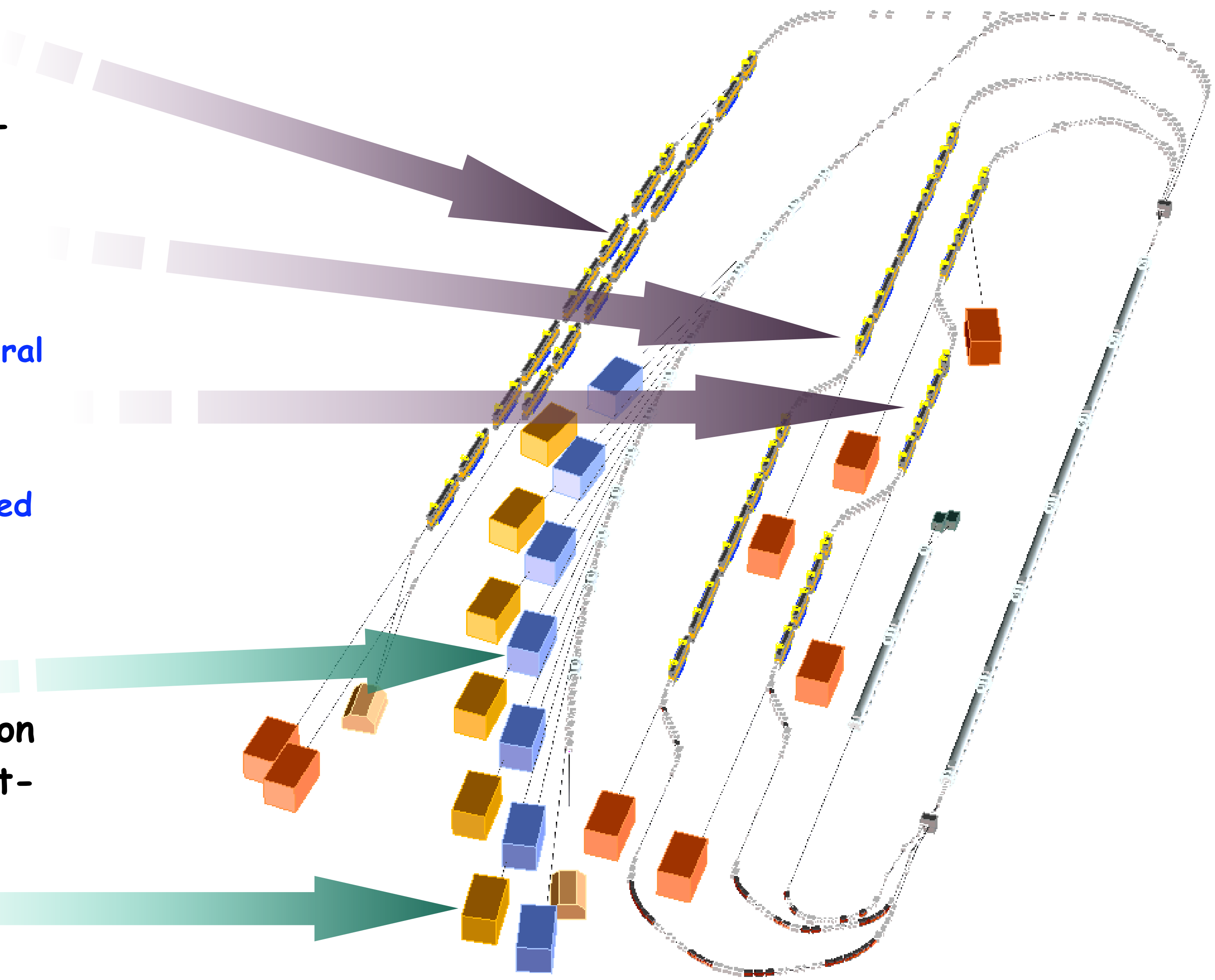
- RF photocathode guns produce high-quality electron beams
  - 2-3 mm-mrad, 1 nC, 30 ps
  - Ability to manipulate the beam emittance
- Compress beam from the injector to 2-3 ps
- Accelerate in multiple passes through linac
- 1-3 GeV beam generates x-rays
  - 10-100 fs x-ray pulses

- Compact (~ 150 x 50 m)
- Flexible configuration
  - Each pass provides opportunities for
    - Manipulation of the electron beam
    - Photon production
      - Multiple beamlines
  - Variable repetition rate
    - Energy recovery option

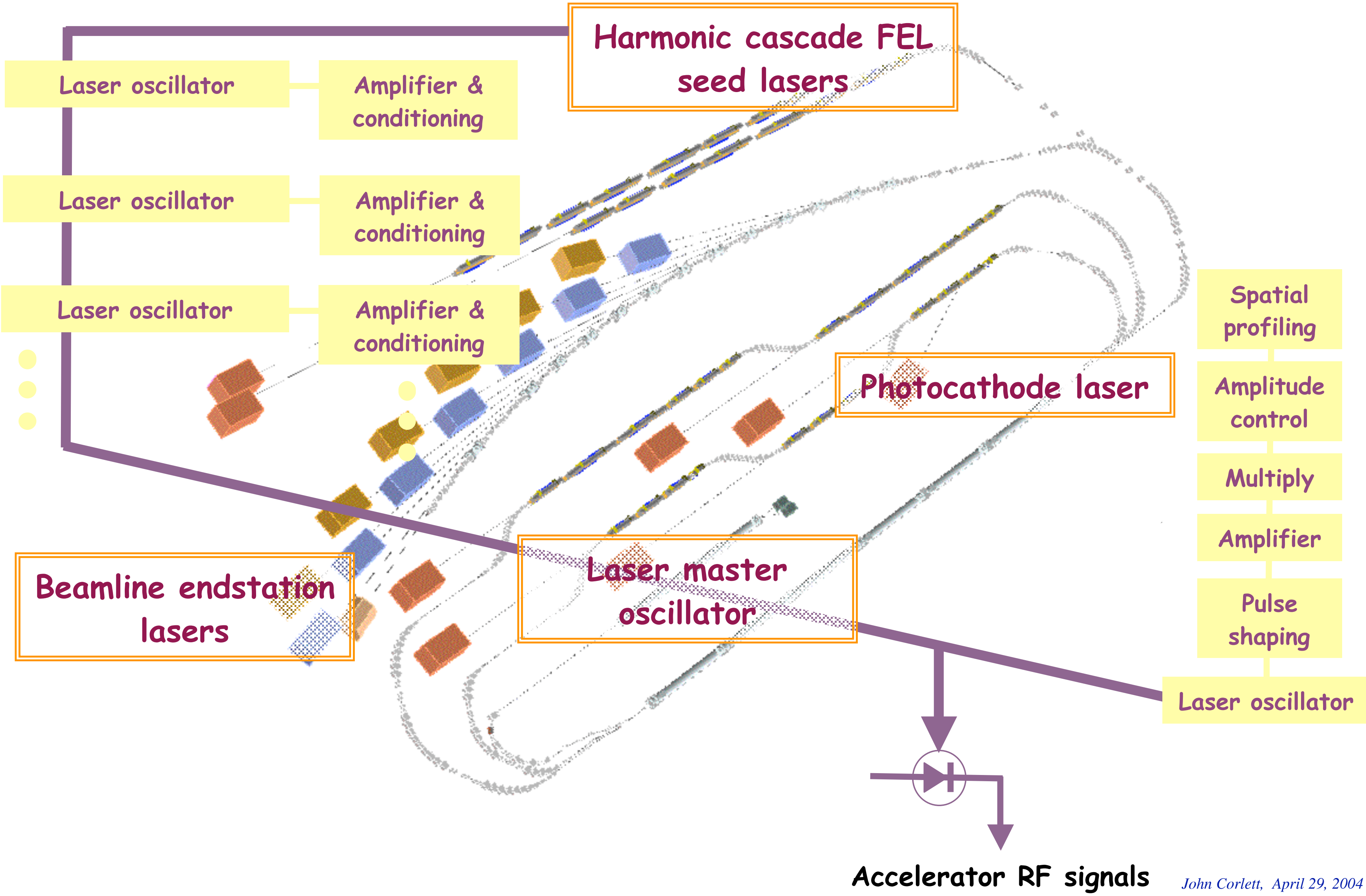
LUX provides tunable ultrafast x-ray pulses for up to ~ 20 beamlines

- Soft x-rays
- Laser-seeded cascaded harmonic-generation in FEL's
- *Not SASE*
  - 20-1000 eV
  - Spatial and temporal coherence
  - 10-100 fs
  - ~ Transform limited

- Hard x-rays
- Spontaneous emission in narrow-gap short-period insertion devices
  - 1-12 keV
  - 50-100 fs

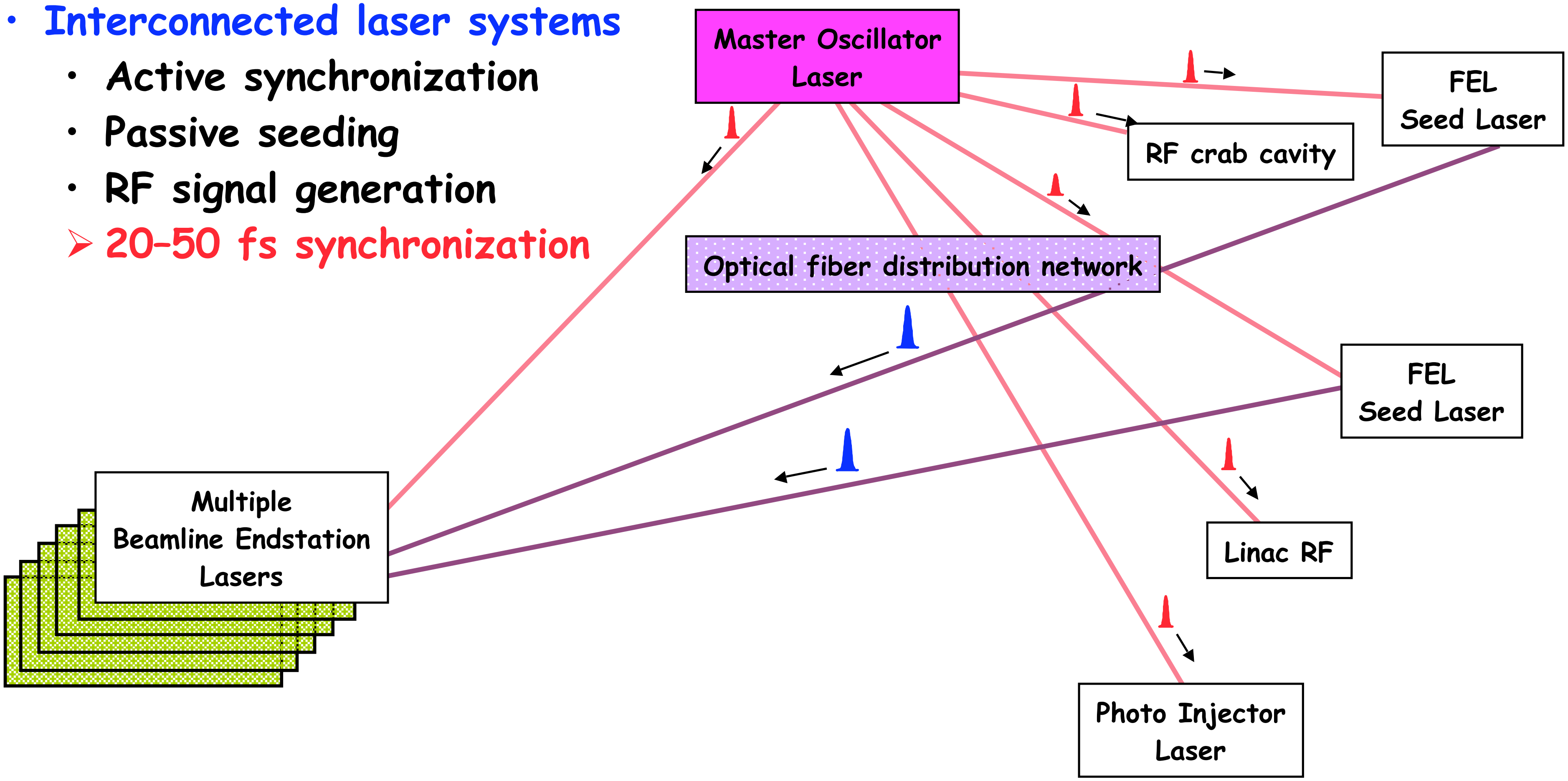


Sophisticated short-pulse laser systems are an integral component of the facility

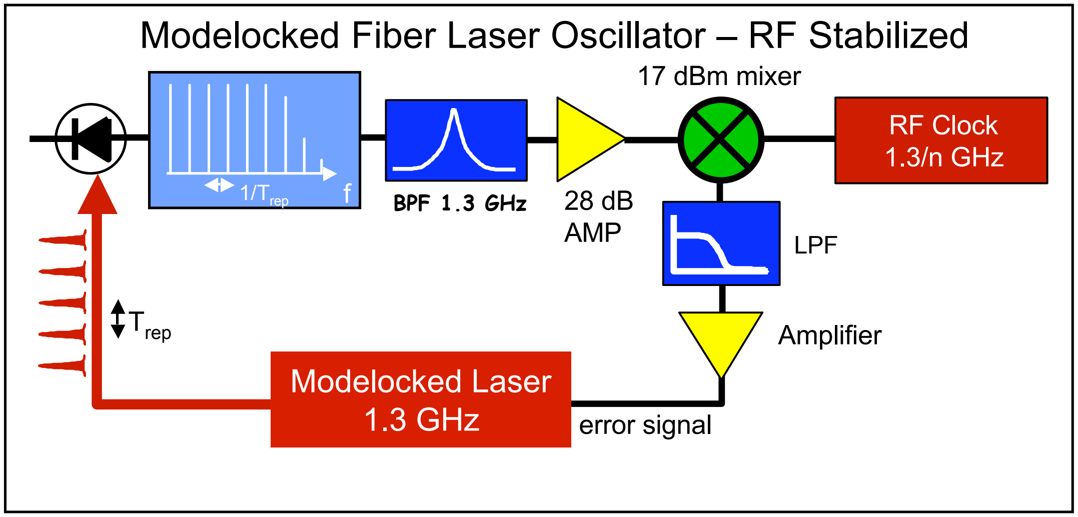


All-optical timing system to achieve synchronization between laser pump and x-ray probe

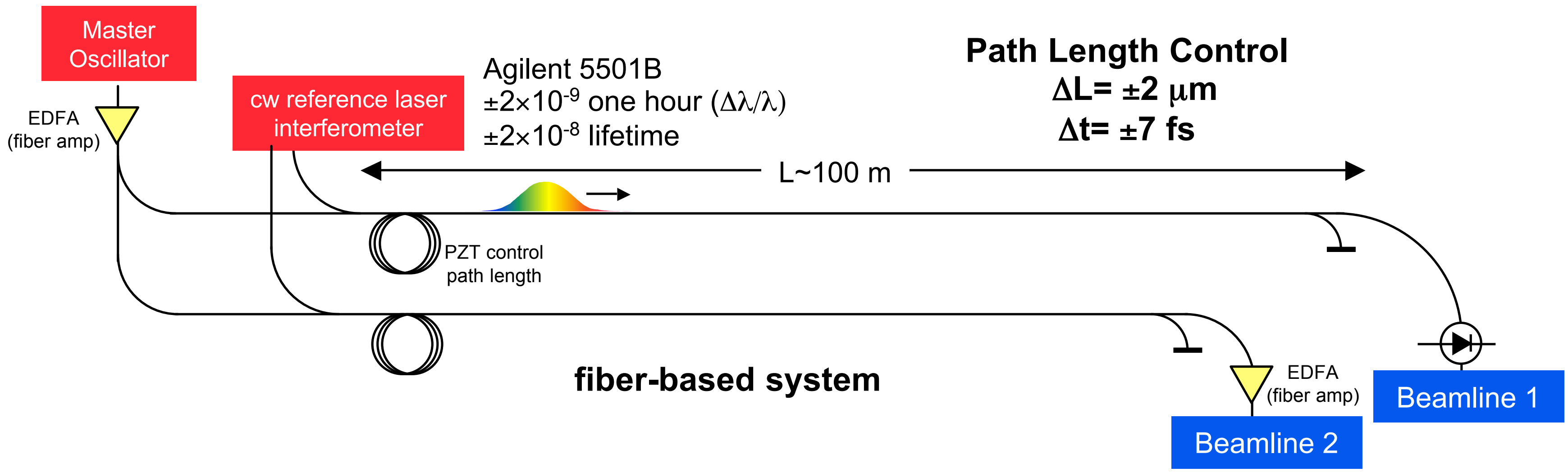
- Laser-based timing system
- Stabilized fiber distribution system
- Interconnected laser systems
  - Active synchronization
  - Passive seeding
  - RF signal generation
  - ➢ 20–50 fs synchronization



Master oscillator and timing distribution



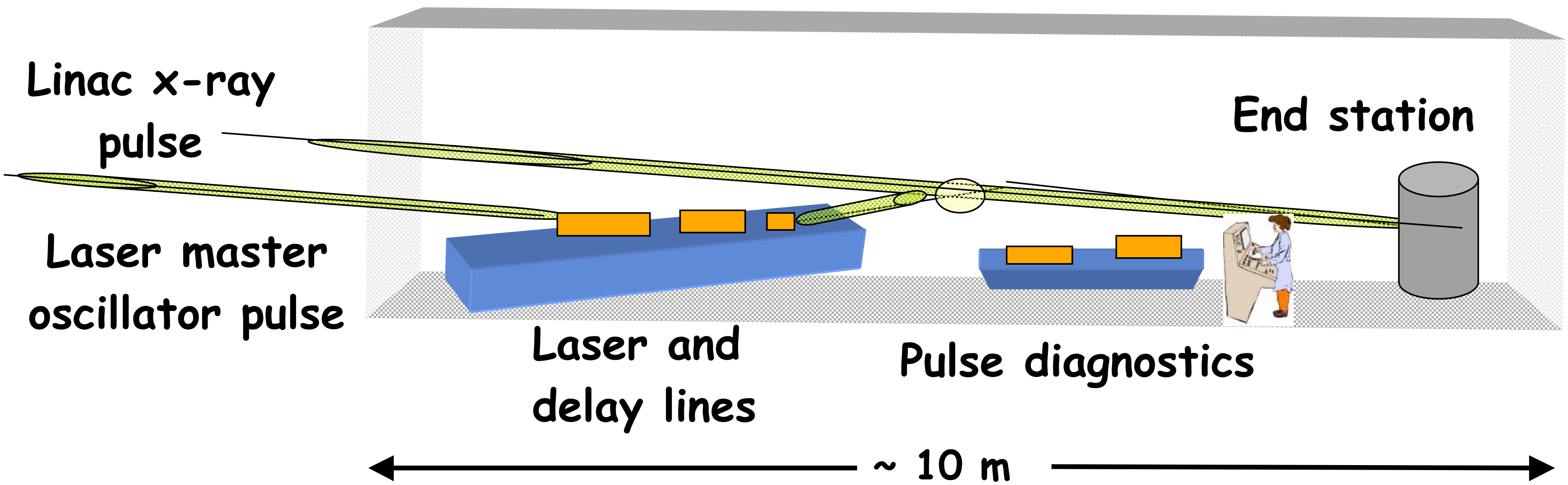
- Phase-lock all lasers to master oscillator
- Derive rf signals from laser oscillator
- Fast feedback to provide local control of accelerator rf systems
  - Synchronization of 20-50 fs



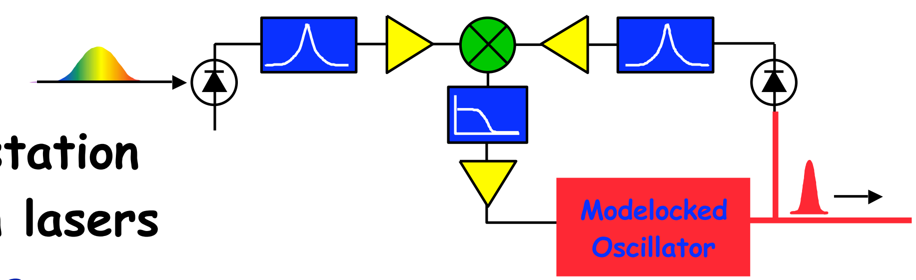
John Corlett, April 29, 2004

Typical end station concept

Precisely timed laser and linac x-ray pulses

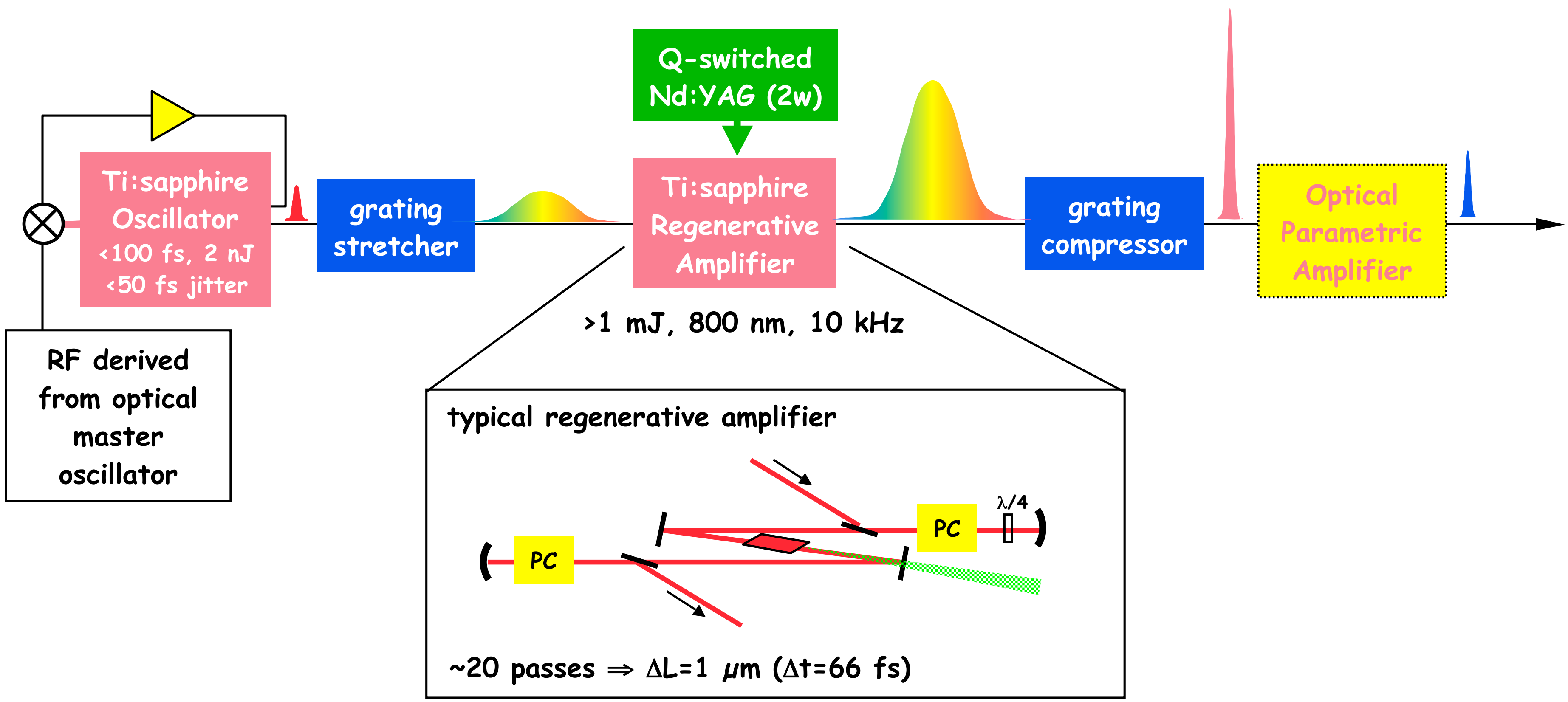


- Active laser synchronization
  - Independent oscillators at each endstation
  - Complete independence of endstation lasers
    - Wavelength, pulse duration, timing, repetition rate etc.



Beamline endstation lasers

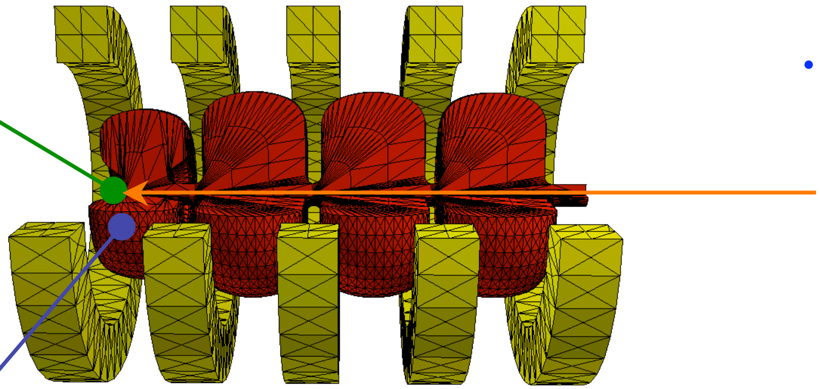
chirped-pulse amplification



- interferometric stabilization
- cross-correlate with oscillator (compress first)
- temperature stabilize (Zerodur or super-invar)

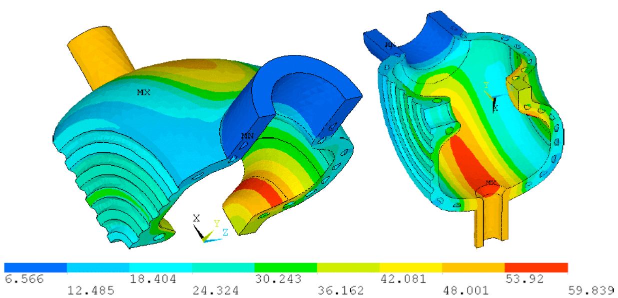
Laser-driven rf photocathode
10 kHz pulse repetition rate

- Cathode
  - Cs_2Te
- RF field
  - 64 MVm^{-1}

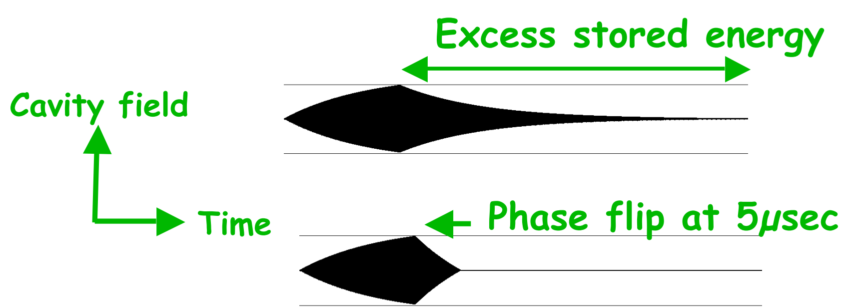


- Laser
  - 1 μJ, 35 ps, 10 kHz, 266 nm
  - Spatial and temporal control to provide low-emittance electron bunches

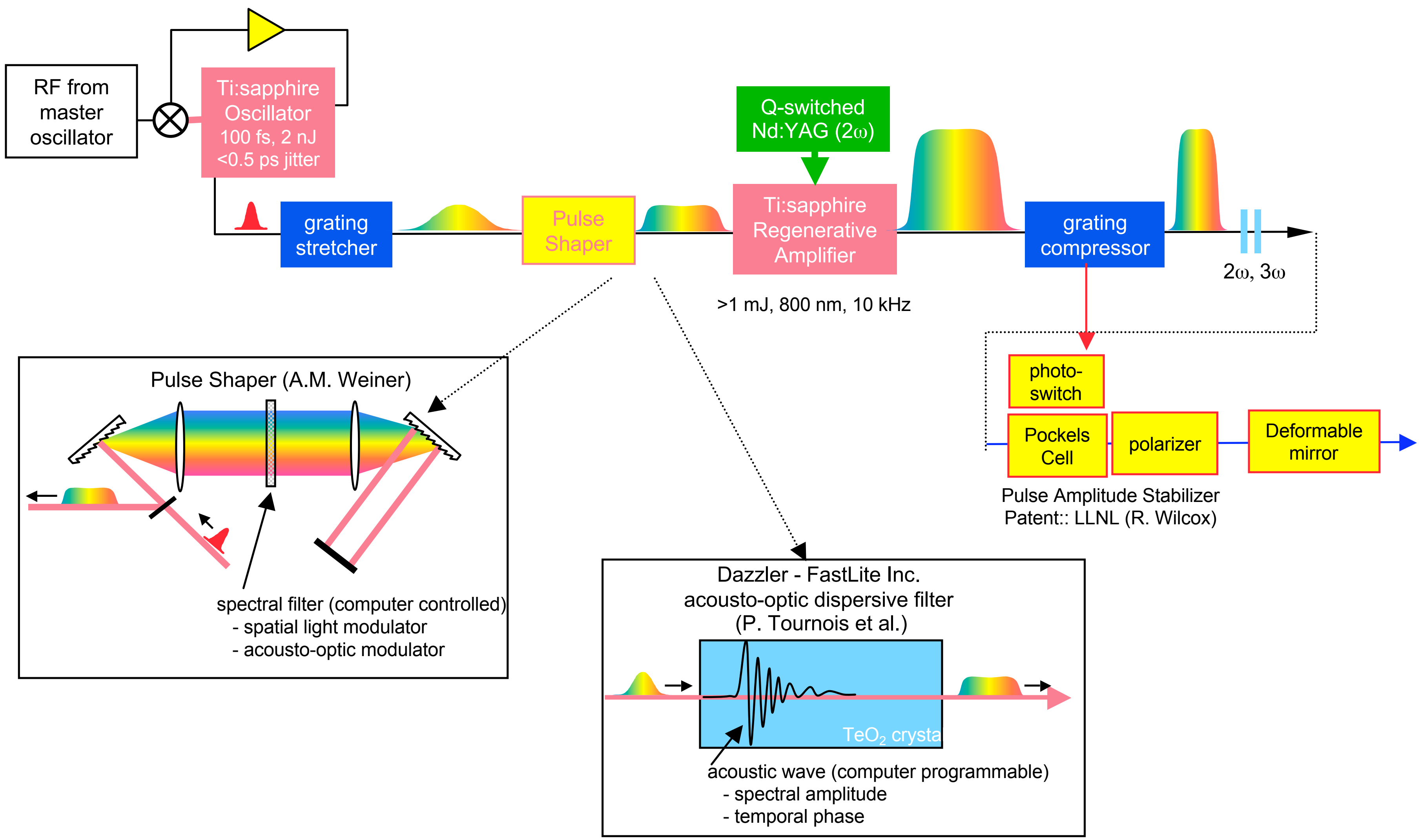
- ANSYS analysis of rf heating and thermal management



- Digital control of rf phase and amplitude
- Active phase control reduces stored energy

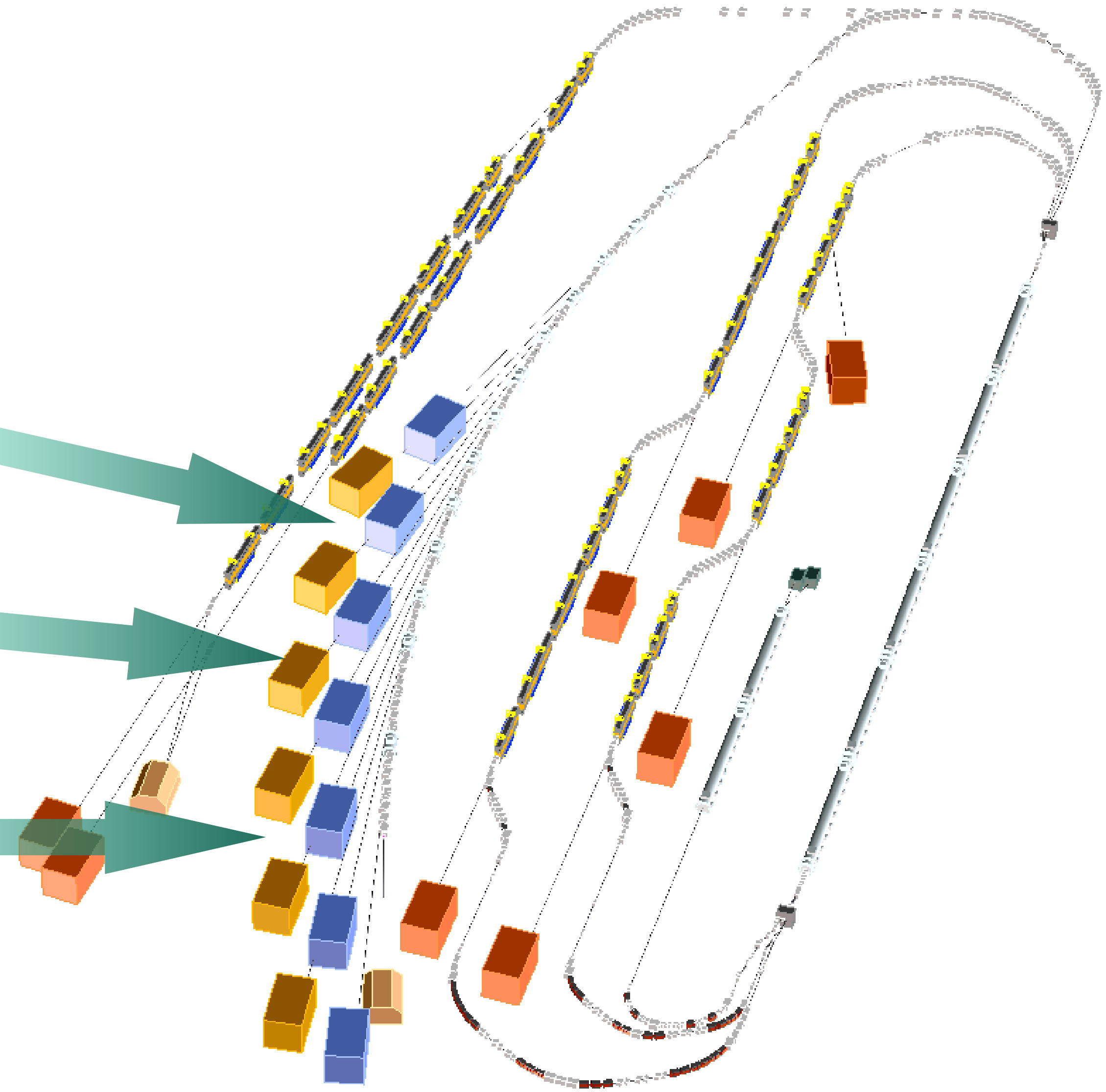


Laser pulse shaping influences the brightness of the emitted electron bunch

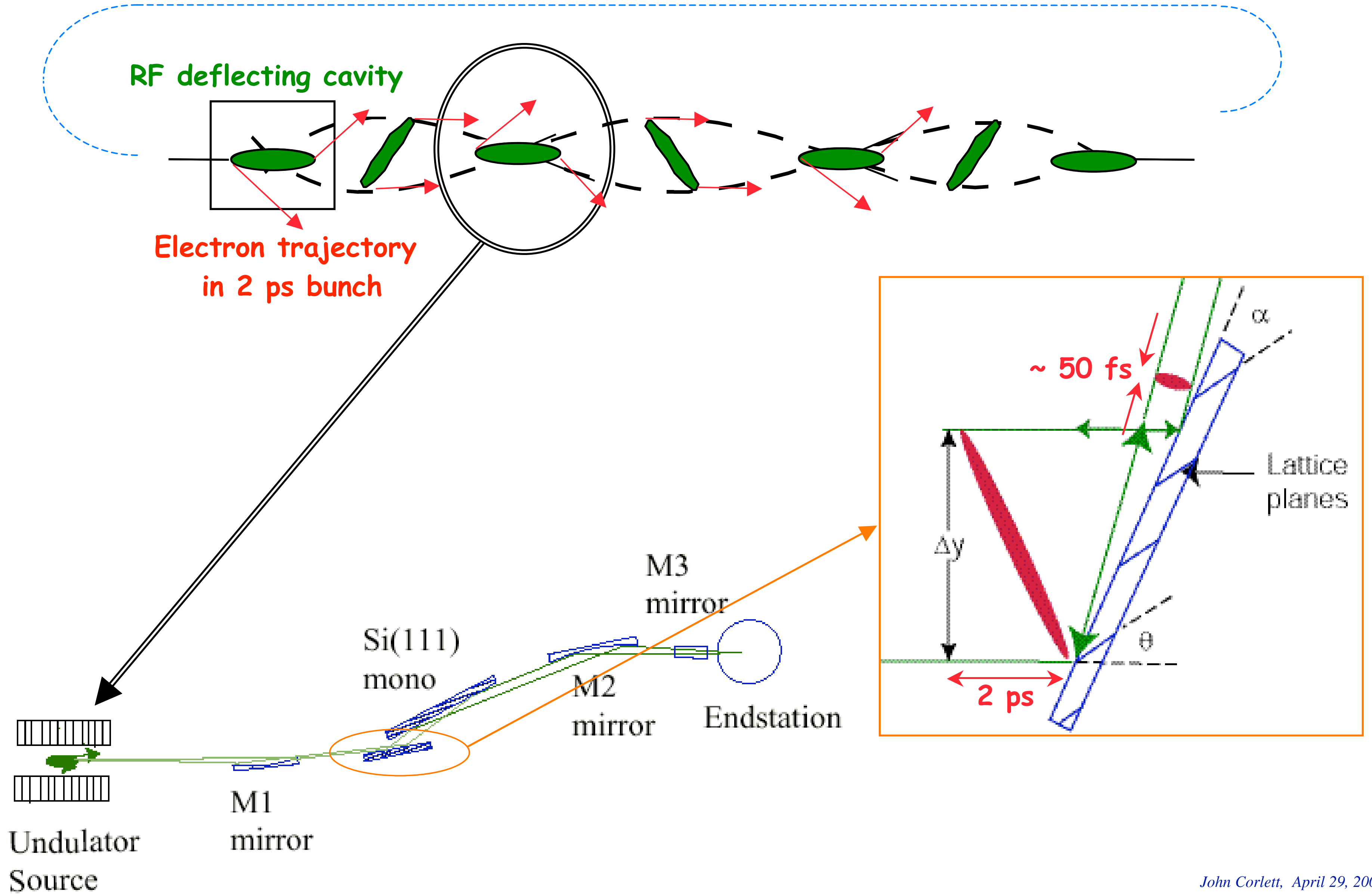


Hard x-rays from spontaneous emission, electron and photon pulse manipulation

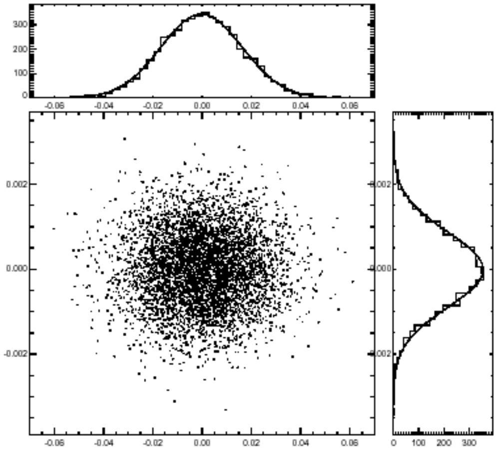
- Hard x-rays
- Spontaneous emission in narrow-gap short-period insertion devices
  - 1-12 keV
  - 50-100 fs



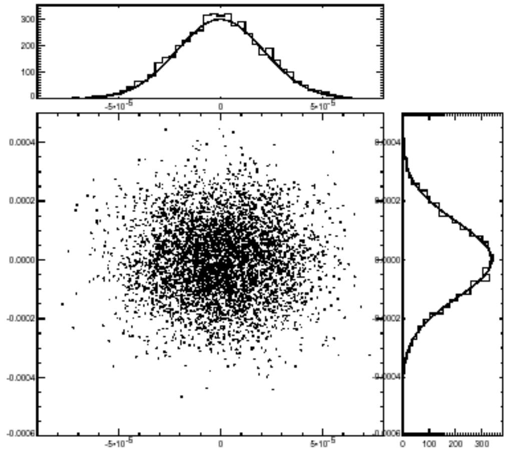
Ultrafast hard x-ray pulses produced by electron bunch manipulation and x-ray compression



Hard x-ray undulator beamline

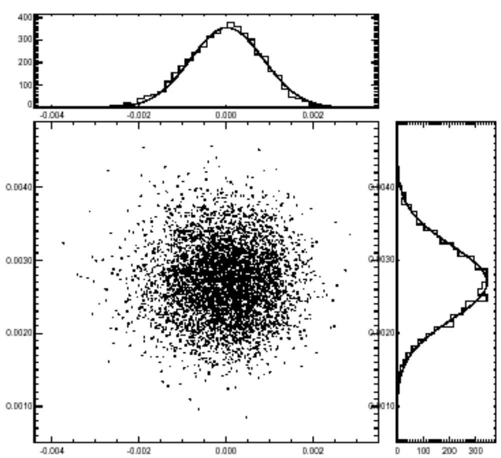


Source dimensions
390 μm (h) x 20 μm (v)

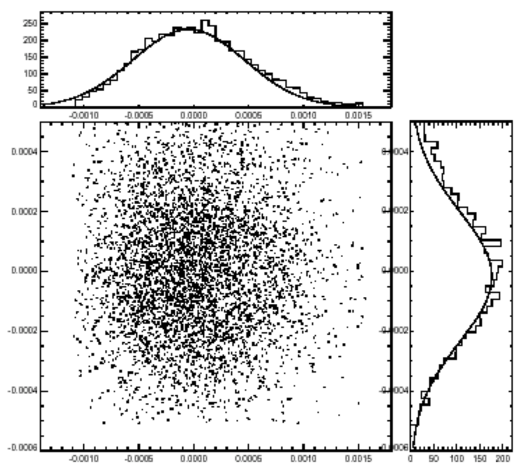


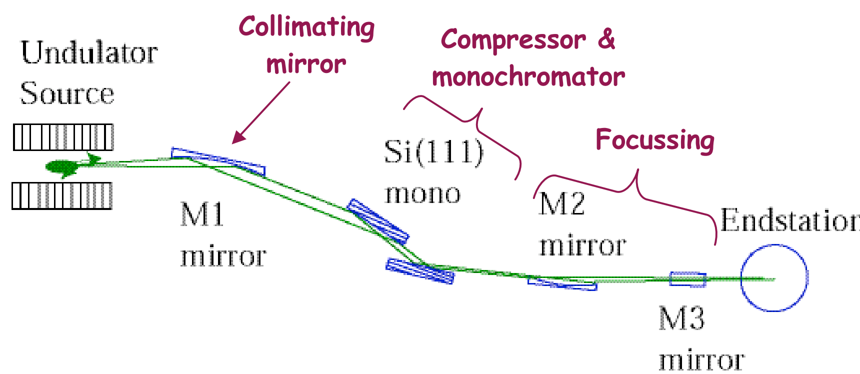
Source divergence
50 μrad (h) x 300 μrad (v)

Focus dimensions
20 μm (h) x 12 μm (v)



Focus divergence
1.2 mrad (h) x 500 μrad (v)





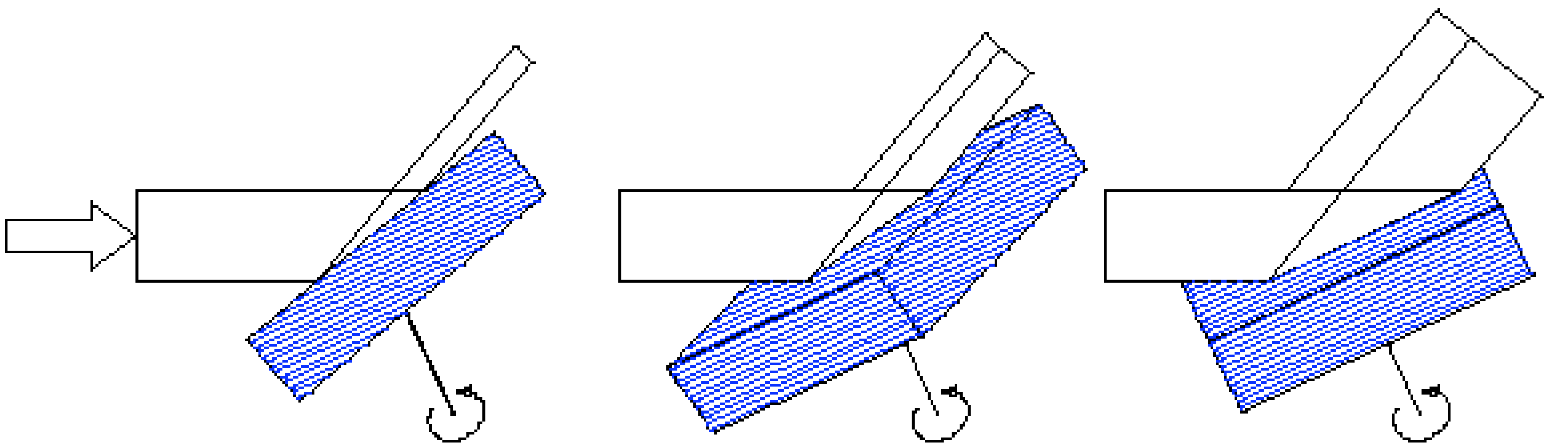
- Conventional optical elements
  - Temporal stability will be important

Poster by P. Heimann

Tuning x-ray pulse compression as a function of photon energy

- X-ray compression $\Delta l = 2\,\Delta y \dfrac{\sin\theta\ \sin\alpha}{\sin(\theta+\alpha)}$
- Add rotation φ about axis normal to Bragg planes (Bragg angle θ)

  $\Longrightarrow$ Variation of crystal asymmetry angle α between Bragg planes and crystal surface, keeping pulse compression fixed



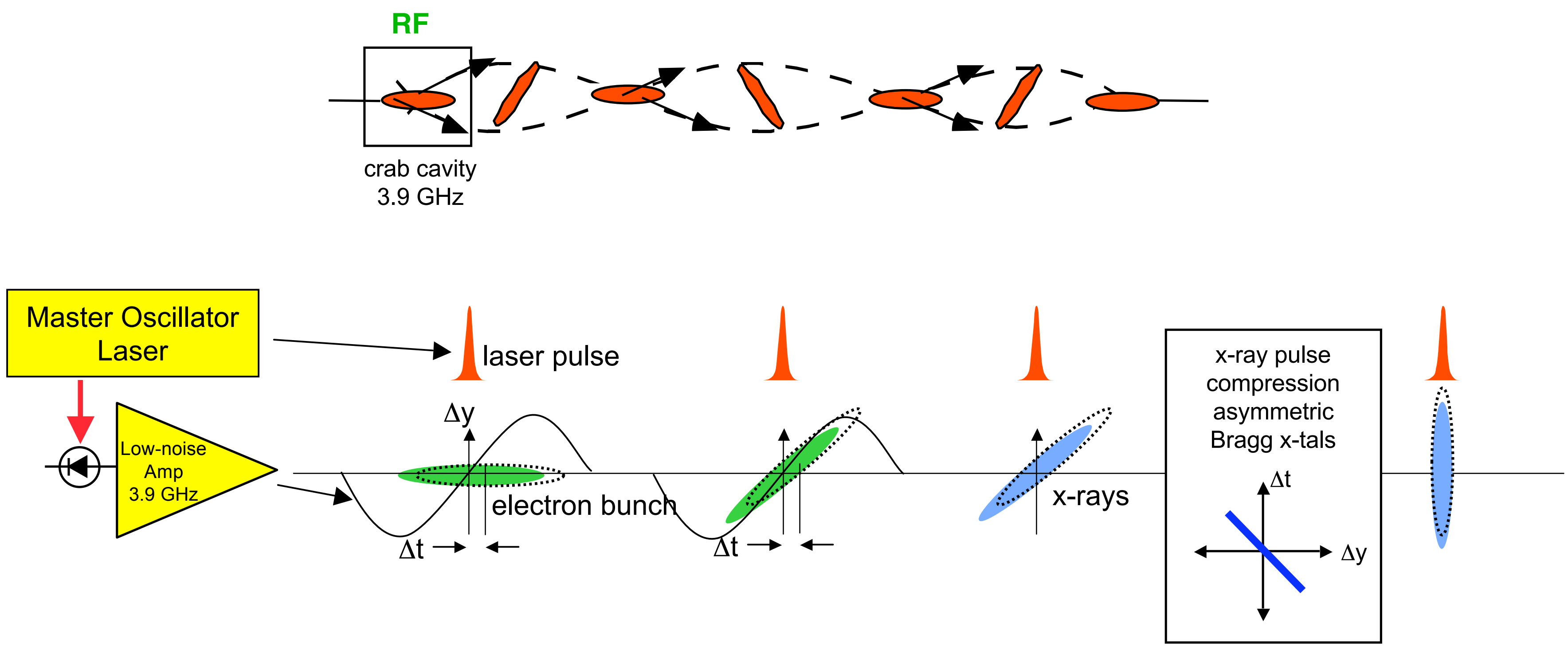
$\varphi = 0°$
$\alpha = 15°$

$\varphi = 45°$
$\alpha = 11°$

$\varphi = 90°$
$\alpha = 0°$

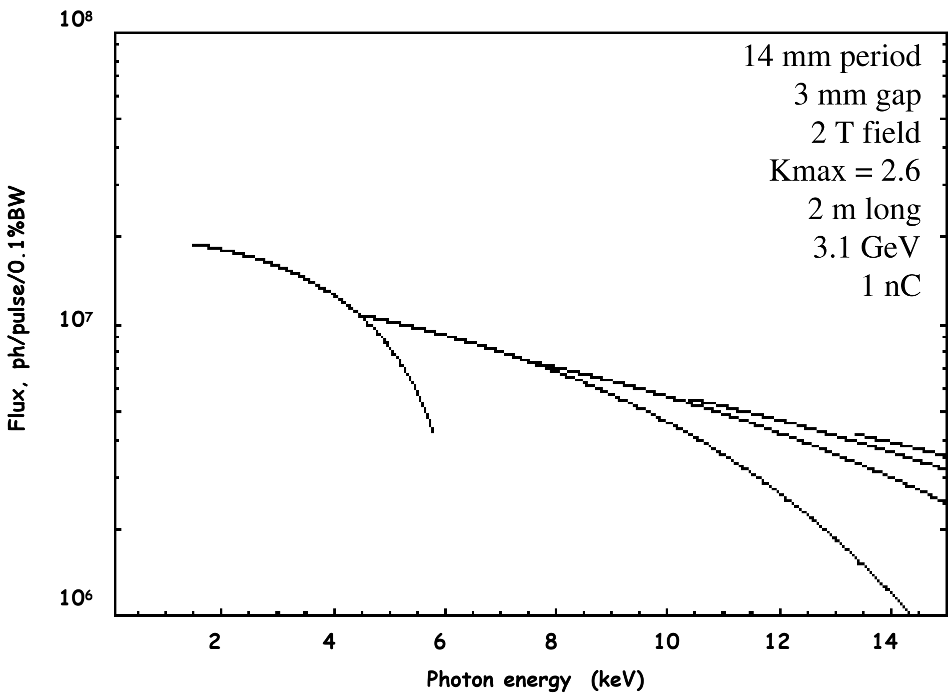
- Limitations
  - Penetration of x-rays into crystal: N λ ~ 1 μm (3 fs) for Si(111) at 8 keV

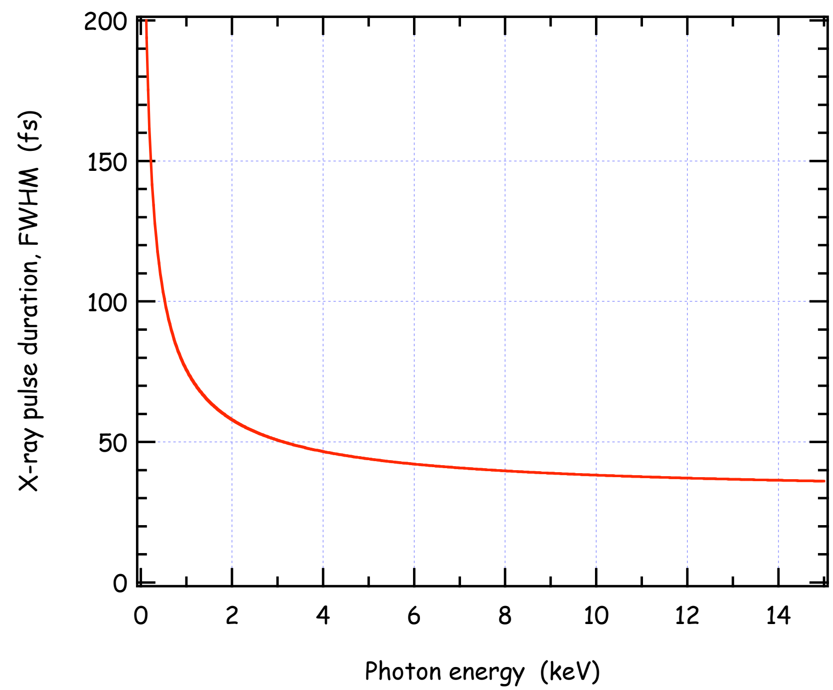
Synchronize deflecting cavities and pump laser for hard x-ray production



- Electron bunch timing jitter ~ 500 fs
- Deflecting cavity phase stability < 0.01°
  - 35 fs contribution from rf phase noise
  - Expect synchronization better than 50 fs

LUX - hard x-ray pulses

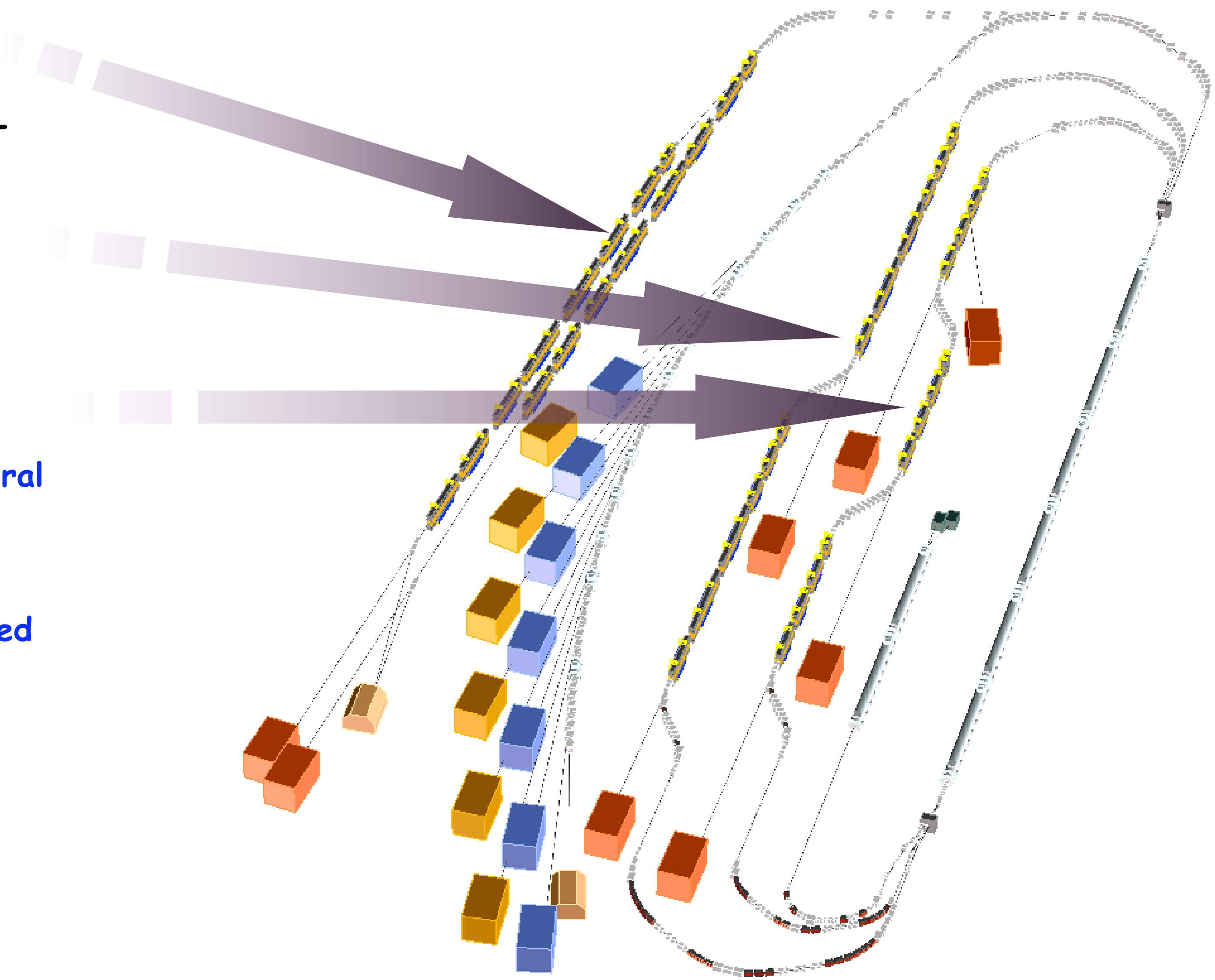




- *Same flux/pulse as 3rd generation light sources*
- *1000 times shorter pulse*

EUV - soft x-rays from harmonic generation in FEL's

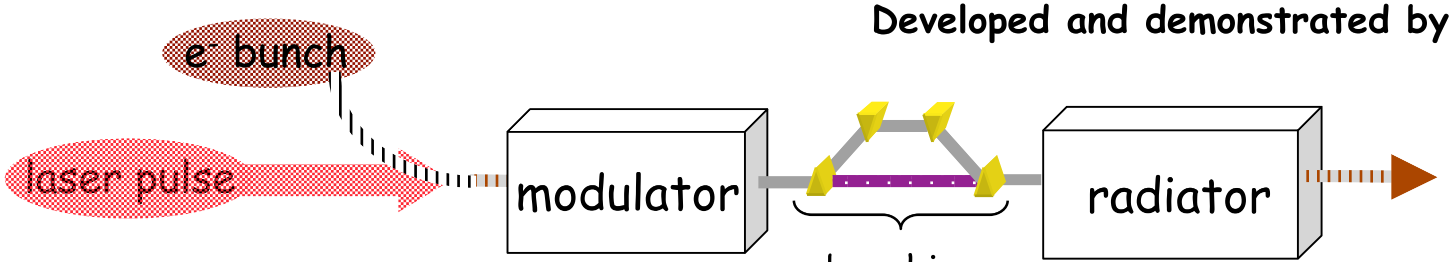
- Soft x-rays
- Laser-seeded cascaded harmonic-generation in FEL's
- *Strong modulation*
- *Low-gain FEL*
- *Not SASE*
  - 20-1000 eV
  - Spatial and temporal coherence
  - 10-100 fs
  - ~ Transform limited



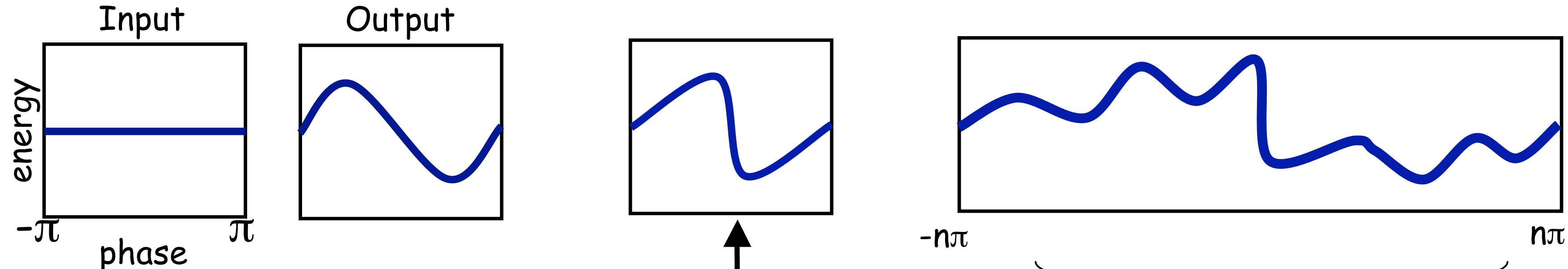
Harmonic generation scheme - coherent source of soft x-rays

Developed and demonstrated by L.-H. Yu et al, BNL [1]

Talk by X.J. Wang



e-beam phase space:



Energy-modulate e-beam in undulator via FEL resonance with coherent input radiation

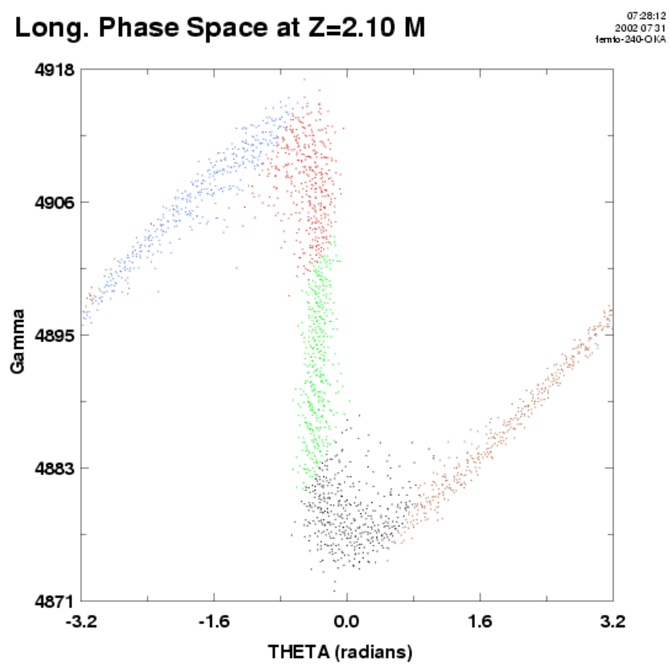
Dispersive section strongly increases bunching at fundamental wavelength and at higher harmonics

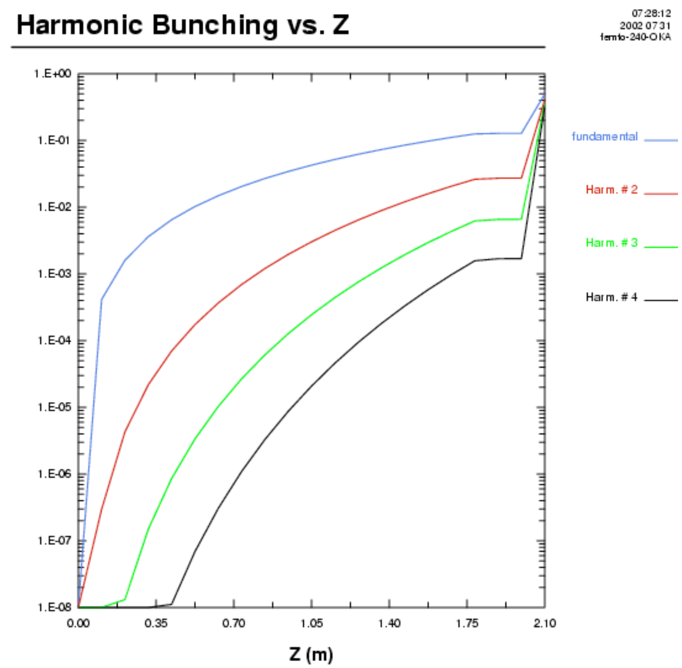
In a downstream undulator resonant at λ_0/n, bunched beam strongly radiates at harmonic via coherent spontaneous emission

[1] L.-H. Yu et al, "High-Gain Harmonic-Generation Free-Electron Laser", Science **289** 932-934 (2000)
[2] L.H. Yu *et al.*, "First Ultraviolet High Gain Harmonic-Generation Free Electron Laser", *Phys. Rev. Let.* Vol 91, No. 7, (2003)

Bunching and harmonic content following λ=240 nm modulator

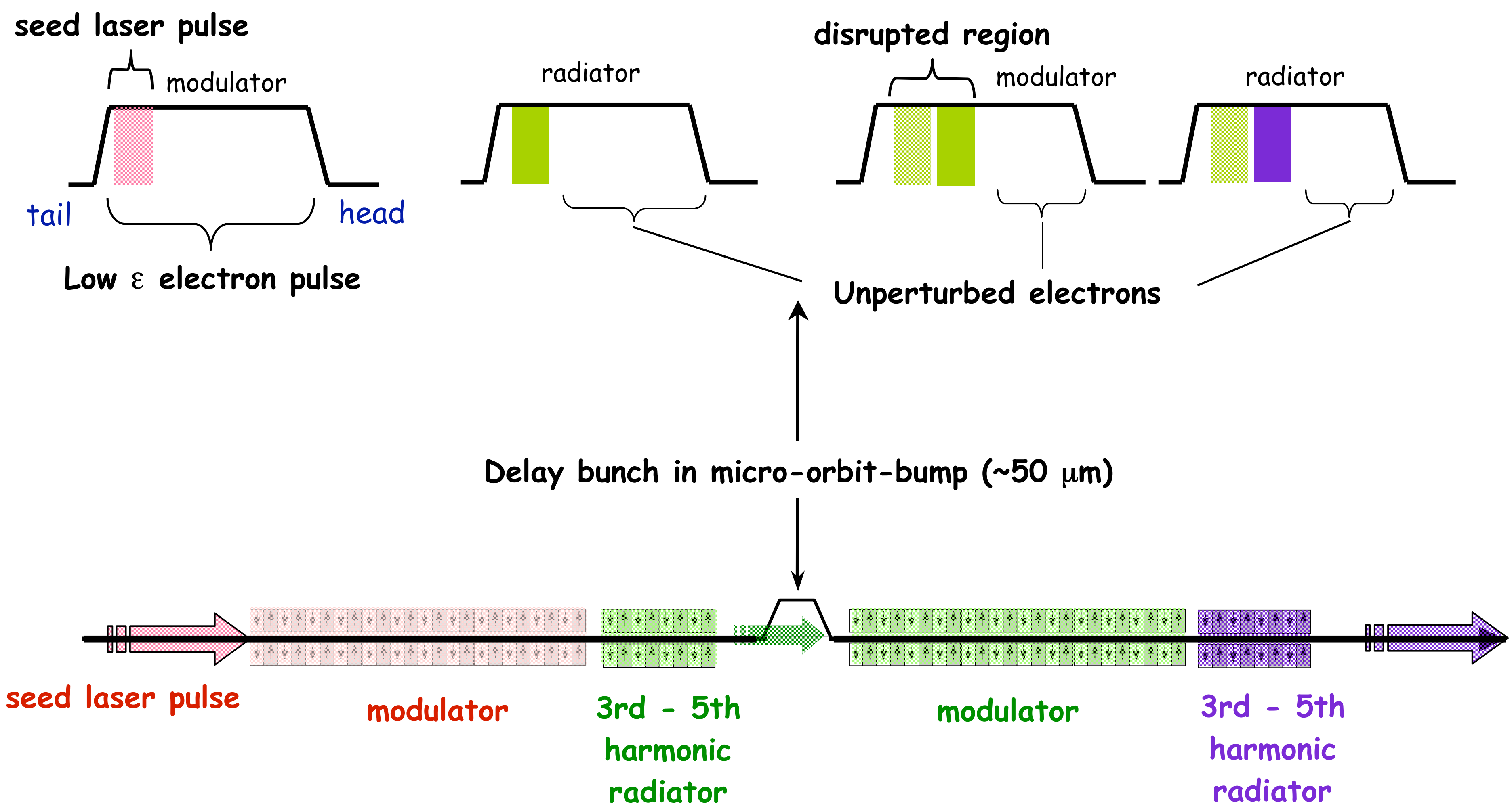
- Strong modulation defines wavelength, timing, and duration of x-ray pulse





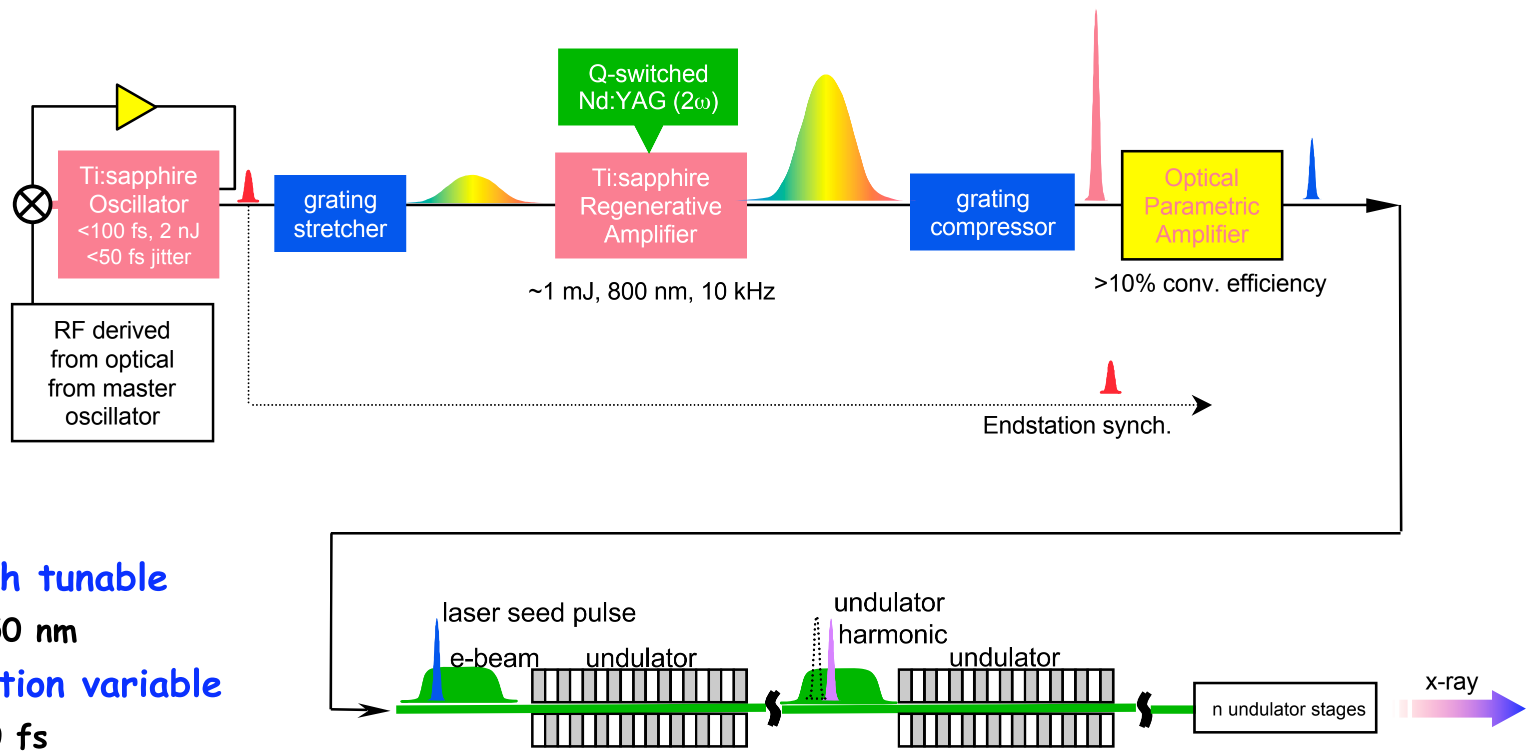
- Low gain regime in radiators
- Output is temporally and spatially coherent and approximately transform limited
- *Different from SASE*
  - Process is initiated and output defined by a seed laser
    - ultra-stable pulse duration
    - synchronized to seed laser
    - temporal coherence imprinted by seed laser

Cascaded harmonic generation scheme



User has control of the FEL x-ray output properties through the seed laser

- OPA provides controlled optical seed for the free electron laser

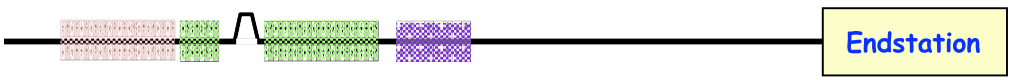


- Wavelength tunable
  - 190-250 nm
- Pulse duration variable
  - 10-200 fs
- Pulse energy
  - 10-25 μJ
- Pulse repetition rate
  - 10 kHz
- Endstation lasers seeded by or synchronized to Ti:sapphire oscillator
  - Tight synchronization <20 fs

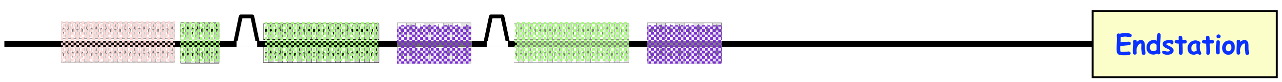
Multiple independent harmonic cascades – independent wavelength tuning for each beamline

20 eV beamline - single stage (4^{th}) harmonic generation

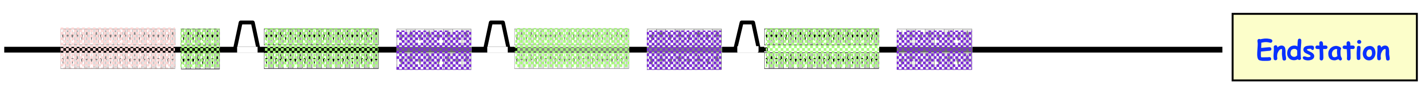
100 eV beamline - two-stage (16^{th}) harmonic generation



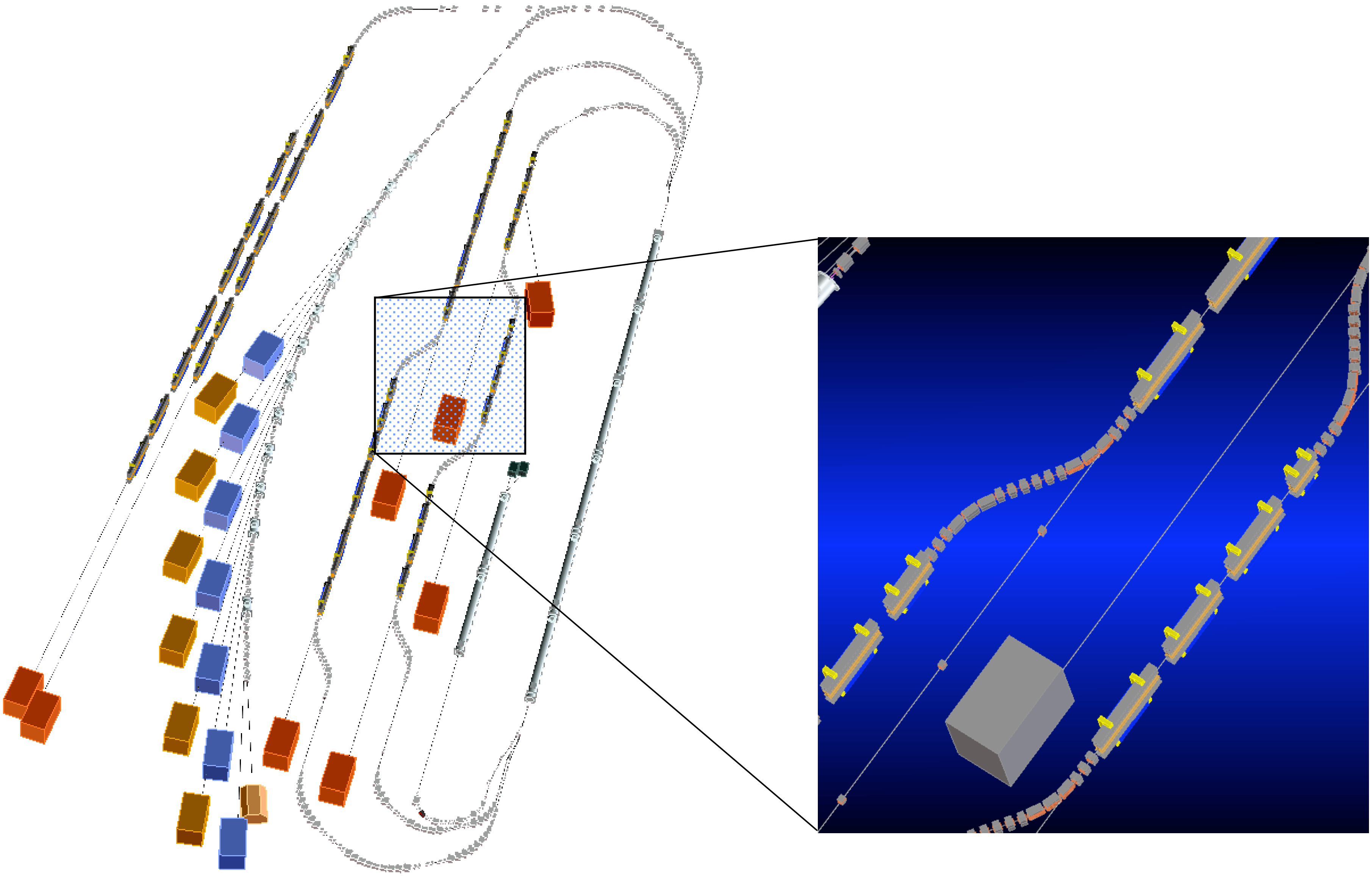
500 eV beamline - three-stage (80^{th}) harmonic generation



1000 eV beamline - four-stage (200^{th}) harmonic generation

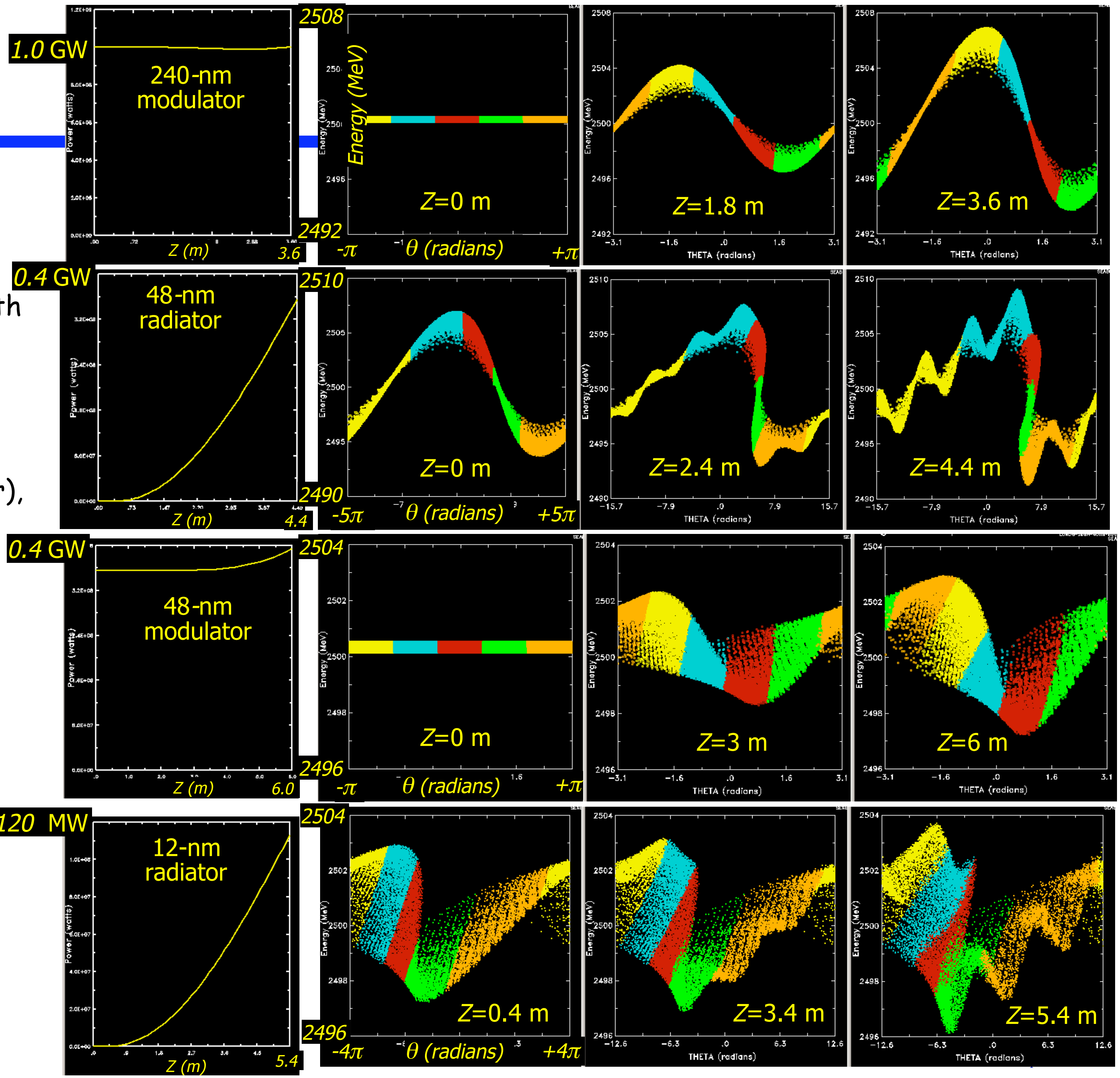


Harmonic cascades



FEL simulations

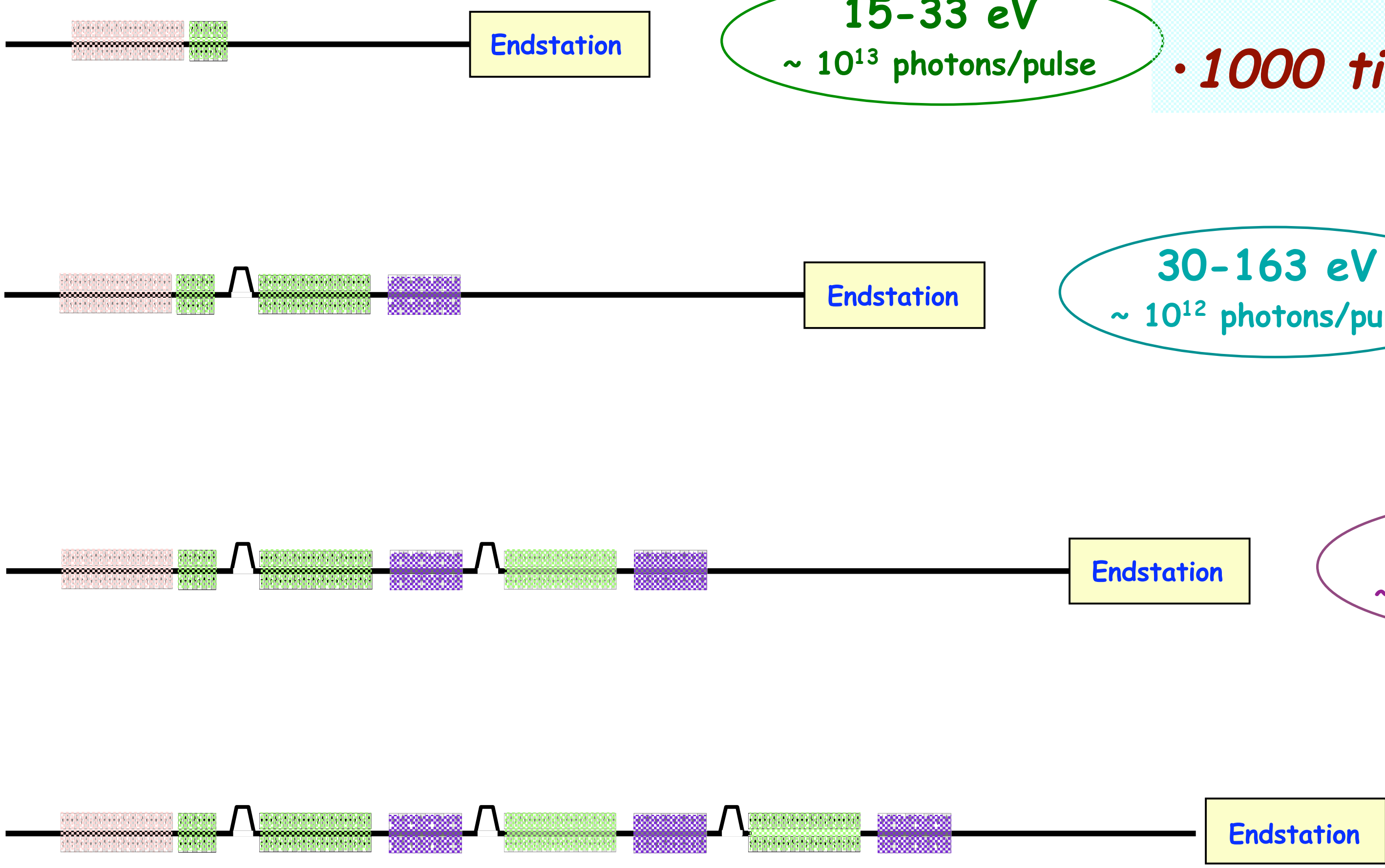
- At each modulator, radiation interacts with "virgin" e^-
- At each harmonic upshift $\lambda \Rightarrow \lambda/n$ (modulator to radiator), macro-particle phase multiplied by n
- Bunching effects of dispersive section visible in change from Z=6 m in 48-nm modulator to Z=0.4m scatter plot in 12-nm radiator



Harmonic cascades - coherent, high-flux,tunable

- *10^3-10^5 times 3rd generation light sources flux/pulse*
- *1000 times shorter pulse*

190-250 nm seed laser
20 μJ in 200 fs



15-33 eV
~ 10^{13} photons/pulse

30-163 eV
~ 10^{12} photons/pulse

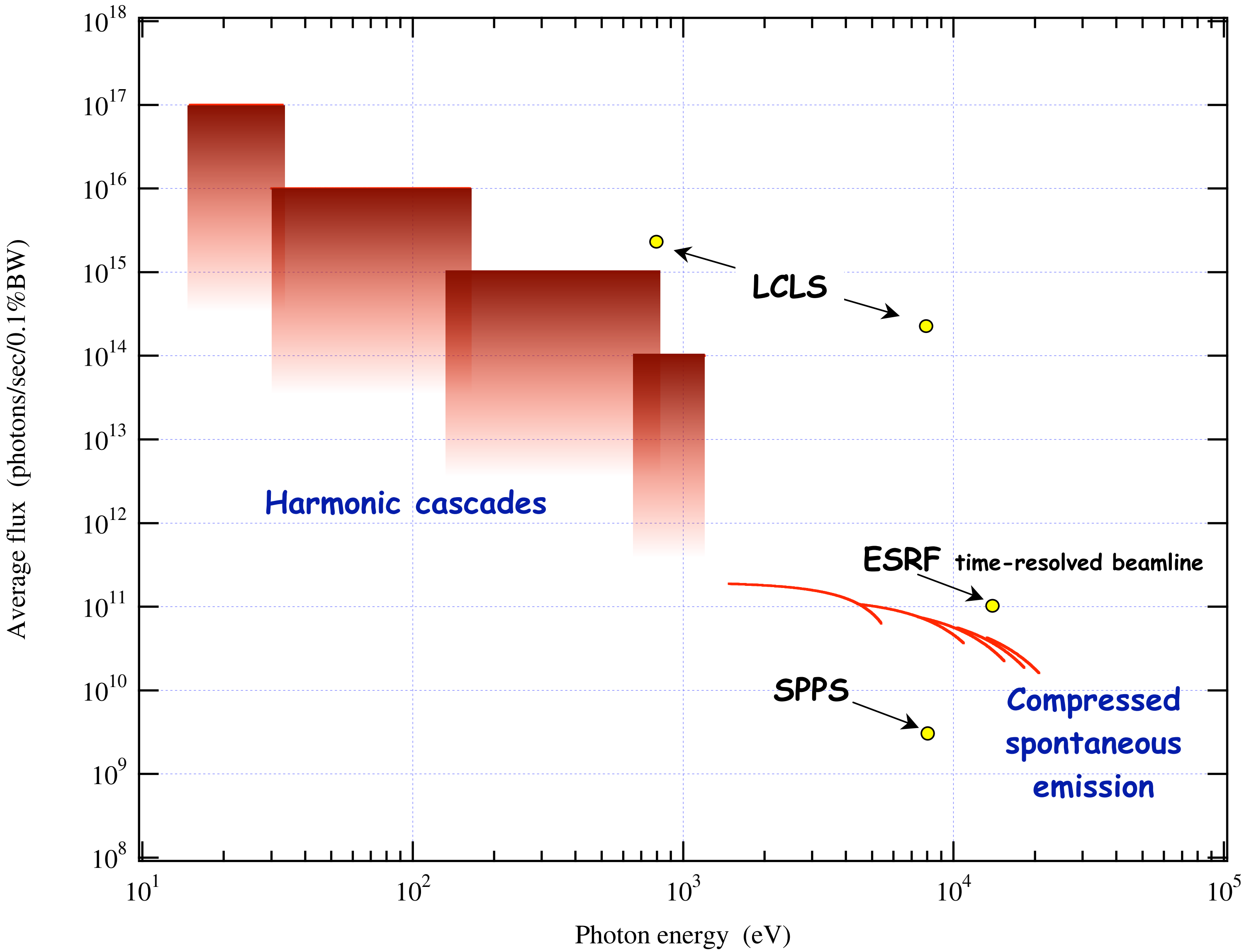
134-816 eV
~ 10^{11} photons/pulse

670-1200 eV
~ 10^{10} photons/pulse

Photon energy requirements

- VUV photoemission of valence states: 15-100 eV
- C, N, and O K-edges: 290 eV, 400 eV, 530 eV
- Fe, Ni, Cu, Zn, Mg, Al, Si: 706 eV, 852 eV, 930 eV, 1020 eV, 1300 eV, 1560 eV, 1840 eV
- Transition metal L-edges: 600-1000 eV
- Diffraction studies >~ 1 keV
- LUX would provide up to 20 independently tunable beamlines offering multiple users flexibility in photon energy
  - Harmonic cascade FEL's 15 eV to 1 keV
  - Compressed spontaneous emission 1-12 keV

LUX flux spectrum



Example - 100 eV photons

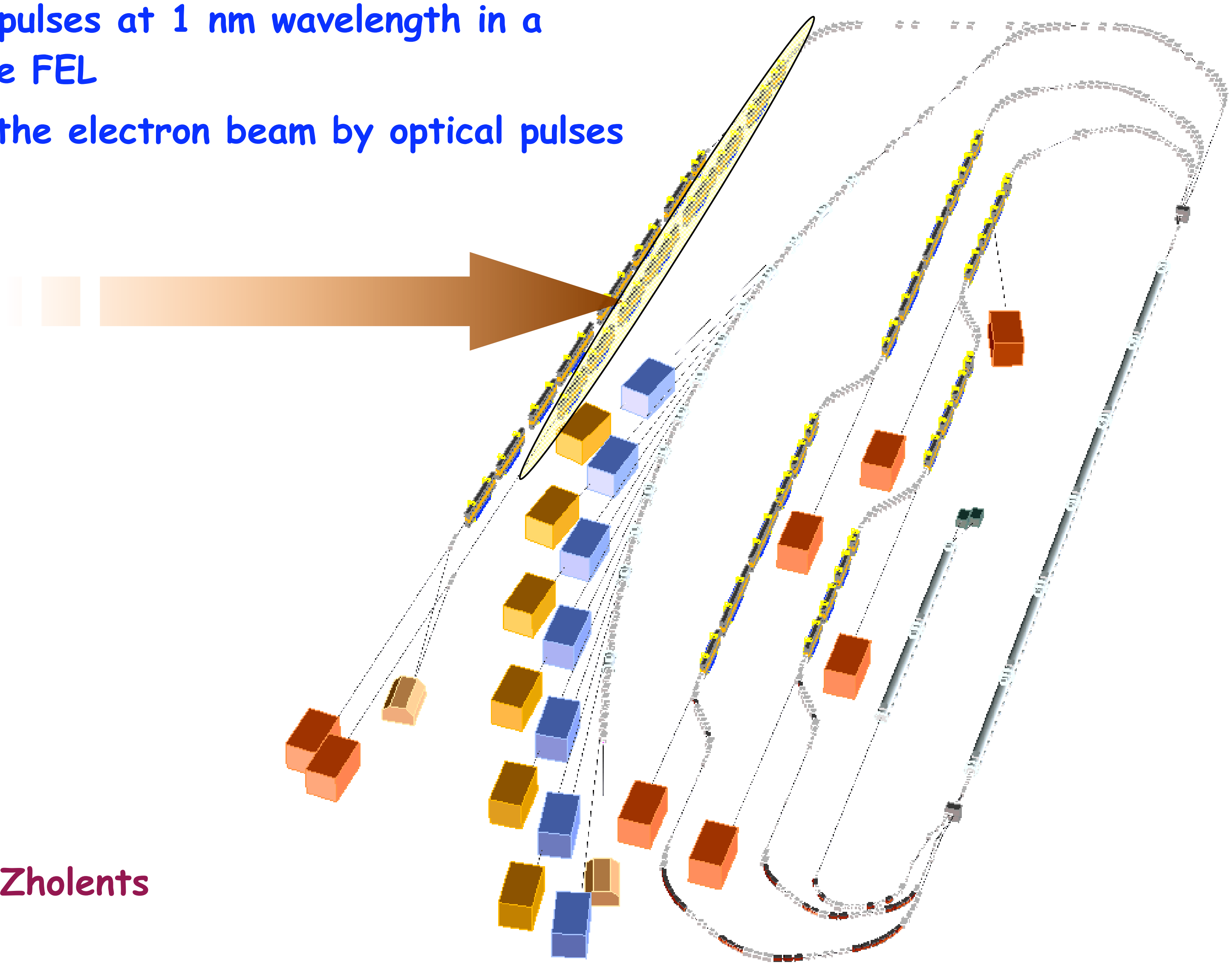
- Two-stage harmonic cascade FEL
  - 1.1 GeV beam energy
  - <25 μJ @ 200 nm seed pulse
- Variable pulse duration
  - 10 fs - 200 fs
- $>10^{11}$ photons in 100 fs, 10^{10} photons in 10 fs
- Approximately transform limited photon pulse (BW $\sim 10^{-4}$ for 100 fs)
  - Grating monochromator bandwidth $\sim 10^{-4}$ gives ~10 meV
- Spatial and temporal coherence
- Repetition rate 10 kHz
- Tuning
  - Change in seed laser wavelength
  - Change in final undulator field, and upstream undulators
- Polarization
  - L, R circular from helical undulator
    - ~ seconds to change polarization
- 20% pulse-pulse fluctuations
    - Average 0.1 % in 3 sec at 10 kHz
- Synchronization
  - 20 fs timing jitter between pump laser and x-ray pulse

Example - 10 keV photons

- Spontaneous emission in narrow-gap undulator
  - 3.1 GeV beam energy
  - 1 nC bunch charge
  - 0.4 mm-mrad vertical emittance
- 5×10^6 photons
- 40 fs FWHM pulse
- Repetition rate 10 kHz
- Radiator bandwidth 0.7%
  - X-ray compression optics bandwidth ~10^{-4} gives ~1 eV
- Tuning
  - X-ray compression optics
  - Change in current of superconducting undulator
- Polarization
  - Linear in plane of undulator
- Few % pulse-pulse fluctuations
  - Average 0.1 % in 1 sec at 10 kHz
- Synchronization
  - 50 fs timing jitter between pump laser and x-ray pulse

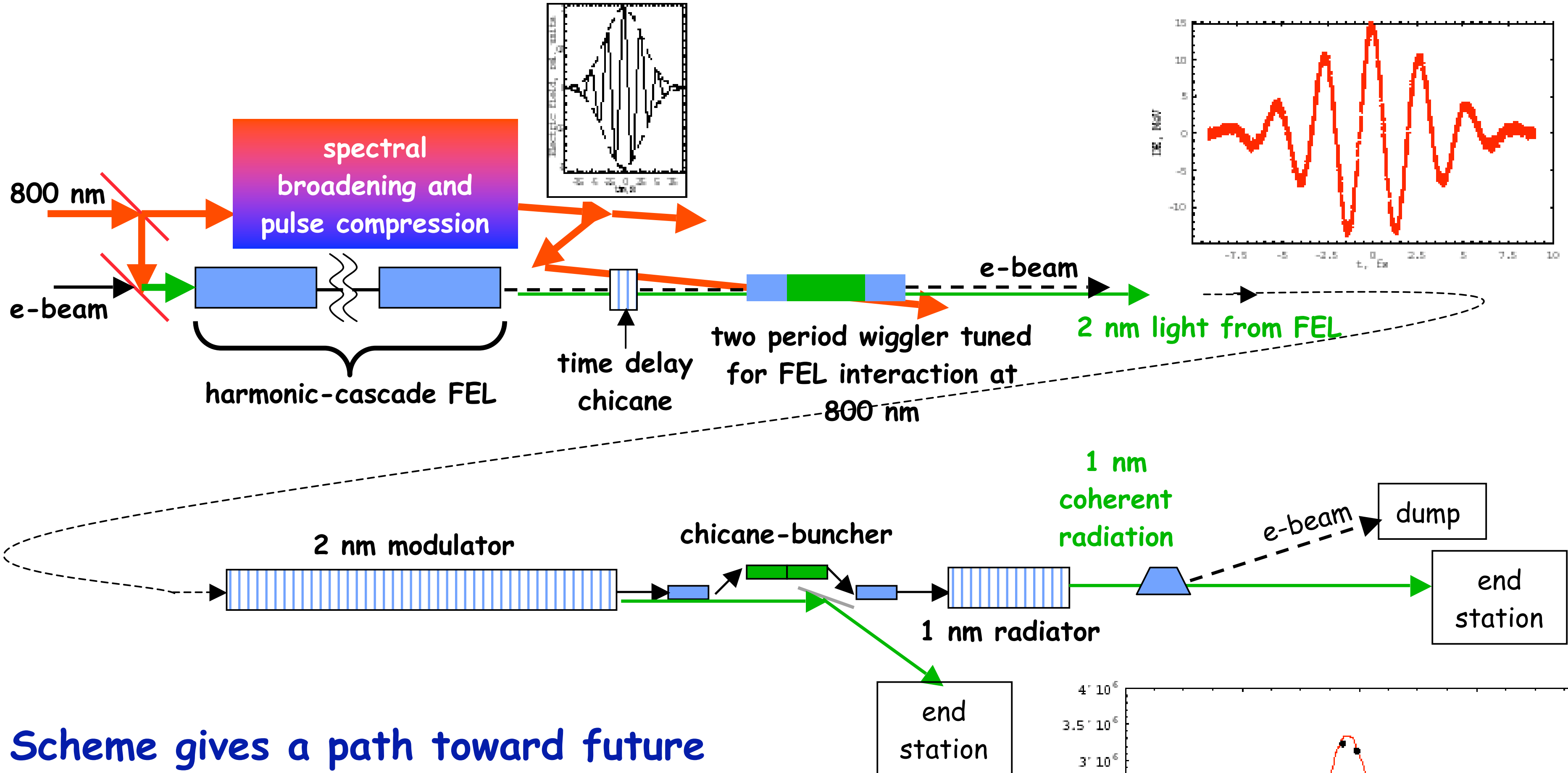
Attosecond x-ray production development line

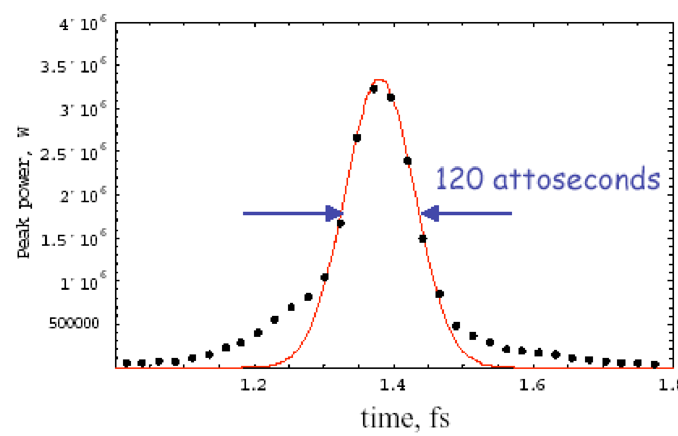
- 100 attosecond pulses at 1 nm wavelength in a harmonic cascade FEL
- Manipulation of the electron beam by optical pulses



- Talk by A. Zholents

Future development - attosecond x-ray pulses





Scheme gives a path toward future attosecond science:

- Timescales for formation of band gaps
- Electron orbital changes
  - Talk by A. Zholents

LUX - proposal for a Linac/laser-based Ultrafast X-ray facility

- LUX is based on a refined, flexible, and upgradeable platform consisting of a recirculating linac and ultrafast laser systems
- Timing and synchronization, matched to laser excitation sources, are central concepts
- Provides versatile ultrafast x-ray experimental capabilities
  - Multiple independently tunable beamlines
  - Ultrashort and coherent pulses
  - Well-characterized outputs
  - Total synchronization
  - Modest powers
  - High signal averaging rates
- Combines diffraction and spectroscopy (nuclear positions and electronic, chemical or structural probes) in the ultrafast x-ray regime, providing a research tool for outstanding new science